DC ELECTRONICS

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LANZAROTE
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DC Electronics, Fifth Edition

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INTRODUCTION

This course in DC, or direct current, electronics presents you with the most important concepts and information necessary to gain a practical working knowledge of the subject today. This is done in the powerfully effective hands-on format that has become a benchmark of all Heathkit Individual Learning Programs.

Beginning with your study of the first unit on electrical current, you will progress through separate units on voltage (unit 2) and resistance (unit 3), to an entire unit (4) that is dedicated exclusively to the most important and fundamental concept in electronics: Ohm's Law. With roughly half of the course dedicated to these concepts, the opportunity to thoroughly learn and advance at a comfortable pace is not only made possible, but facilitated. The twelve hands-on experiments integrated into these first four units include topics on measuring current, voltage, and resistance; voltage rises and drops, shorts and opens, the resistor color code, using the ohmmeter, a light dependent resistor, verifying Ohm's Law, power, and the maximum power transfer theorem.

Once you have gained a solid understanding of the material in the first half of the course, your learning will continue with a study of magnetism in unit 5. Here, you will be presented with both theoretical and practical information that will allow you to understand and work with electromagnetism and electromagnetic devices as applied in the experiments.

To complete your understanding of the essential topic of electrical measurements, unit 6 is concerned entirely with this subject. It includes discussions on the mechanics and internal workings of electronic voltage, current, and resistance meters, as well as a presentation of electronic multimeters. Two experiments are included in this unit. These allow you to determine the sensitivity and loading effects of your meter, while understanding the implications of these.

Unit 7 contains a presentation of DC circuits and the fundamental network theorems. Included are series, parallel, and combination circuits, voltage dividers, current dividers, and bridge circuits, as well as Kirchhoff's laws, the superposition theorem, and Thevenin's and Norton's Theorems.

The course concludes with unit 8 on inductance and capacitance. While the nature of inductance and capacitance, along with the DC characteristics of inductors and capacitors, is the main topic of importance here, this unit serves as an appropriate lead-in to topics beyond the scope of this course which are related to AC (alternating current) electronics.

Whether your learning goals are satisfied by this course in DC, or you are using this as an introduction to the ever expanding "universe" of electronics, we encourage, congratulate, and welcome you.

Course Prerequisites

This is an introductory course in direct current electronics. As such, there is no formal course prerequisite.* Because the course was designed to be effective using a minimum of math, no extensive knowledge of it is required or assumed. Since you will be performing calculations in connection with much of the material, however, a background in simple arithmetic is recommended. This would include addition, subtraction, multiplication, and division of whole numbers and fractions, as well as an understanding of positive and negative numbers. Some x-y type graphs that show the relationship between two quantities are also used along with certain units and dimensions; many of these will be explained in the course (Appendix A contains the basics of scientific notation and powers of ten). Finally, although not required, a basic understanding of introductory algebra can make the formulas, such as Ohm's law, and the power formulas, easier to remember and work with. You may find a basic four-function calculator helpful (but is not required).

Course Structure

You will find two types of objectives in this course. Broad "Course Objectives" are listed after this Introduction. They give a general overview of the goals of the course. More specific "Unit Objectives" are listed near the front of each unit. They tell you exactly what you will be able to do as a result of studying that unit. This lets you maintain a constant check of your progress through the course.

Each unit is divided into sections. A self-test review is included at the end of each section. This gives you an opportunity to evaluate your progress and pinpoint any areas that need review.

Begin your study with Unit 1. Open the unit and read the "Unit Objectives." The "Unit Activity Guide" is on the next page. As the name implies, the activity guide directs you through the unit. A box is provided for each section so that, when you complete a section, you can check it off. If there are any doubts as to what to do next, turn to the activity guide and follow the instructions given there.

* As a supplement, the EEA-3101A audio/visual package highlights and enhances learning of the most important concepts in this course. While this package is not necessary, it can provide useful educational support.

Experiments

Perhaps the most effective way to reinforce a theoretical concept is to demonstrate it a practical experiment. Therefore, each unit contains a number of experiments to illustrate main concepts, and important ideas. These should be performed (or even reperformed) with great care and patience. However, you will probably find yourself looking forward to these. They are designed to be enjoyable, and even fun!

The experiments will work on a wide variety of Heathkit Trainers. These include the ET-3100 series, ET-3600s, and the ET-1000.

Testing

A thorough examination is provided at the end of each unit to test your understanding of the material in that particular unit. These examinations are multiple choice format and the instructions to perform them are self-explanatory. When you complete the examination, compare your answers to the examination answers that follow. After you complete all of the units, you will have the knowledge and skills you set out to obtain. However, there is one final step you should perform—take the **"Final Examination."**

We urge you to take the Final Examination for several reasons. First, it is an excellent learning activity. Not only does it test your knowledge, but it also provides an excellent review of the material you have covered. Another reason to take the final is recognition of your efforts to learn. When you receive a passing grade on your final exam, you will be awarded with an attractive (diploma like) **Certificate of Achievement** and a number of **"Continuing Education Units"** of credit. These CEUs are a nationally recognized method of measuring and recording your participation in an adult education program. To receive your certificate and CEUs, follow the directions in the Final Examination Package.

COURSE OBJECTIVES

When you complete this course, you will be able to do the following:

1. Solve basic electronic problems involving current, voltage, resistance, and power.

2. Explain the relationship between current, voltage, resistance, and power.

3. Discuss the relationship between electricity and magnetism.

4. Use a schematic diagram as a guide to construct DC circuits with components such as resistors, relays, switches, lamps, batteries, and capacitors.

5. Given a wiring diagram of a circuit containing components such as resistors, relays, switches, lamps, batteries, and capacitors, draw an equivalent schematic diagram.

6. Use a multimeter to measure current, voltage, and resistance.

7. Describe the construction, operation, and purpose of resistors, potentiometers, switches, fuses, relays, capacitors, inductors, and batteries.

8. State the basic safety procedures designed to protect you and your test equipment.

9. Build and experiment with basic DC circuits of your own design.

COURSE OUTLINE

UNIT 1 CURRENT

- I. Introduction
- II. Unit Objectives
- III. Unit Activity Guide
- IV. Composition of Matter
  - A. Elements and Compounds
  - B. Atoms
  - C. Electrons, Protons, and Neutrons
  - D. Bohr Model of an Atom
  - E. Difference Between Elements
  - F. The Balanced Atom
- V. Electrostatics
  - A. The Electrical Charge
  - B. Law of Electrical Charges
  - C. The Ion
  - D. Action of Electrostatic Charges
- VI. Current Flow
  - A. Freeing Electrons
  - B. Conductors and Insulators
  - C. The Battery
  - D. Random Drift and Directed Drift
- VII. The Electric Circuit
- VIII. Measuring Current
  - A. The Coulomb
  - B. Powers of Ten and Scientific Notation
  - C. The Ampere
  - D. The Ammeter
- IX. Experiment 1: Measuring Current
- X. Summary
- XI. Unit Examination
- XII. Examination Answers

UNIT 2 VOLTAGE

I. Introduction

II. Unit Objectives

III. Unit Activity Guide

IV. Electrical Force
  - A. Electromotive Force (EMF)
  - B. Potential Difference
  - C. Voltage

V. Producing EMF
  - A. Magnetism
  - B. Chemical
  - C. Friction
  - D. Light
  - E. Pressure
  - F. Heat
  - G. Effects of Emf

VI. Batteries
  - A. Dry Cell
  - B. Lead Acid Battery

VII. Connecting Batteries
  - A. Series Aiding Connection
  - B. Series Opposing Connection
  - C. Parallel Connection
  - D. Series-Parallel Connection

VIII. Voltage Rises and Voltage Drops
  - A. Voltage Rise
  - B. Voltage Drop
  - C. Voltage Drops Equal Voltage Rises

IX. Concept of Ground

X. Measuring Voltage

XI. Experiment 2: Measuring Voltage

XII. Experiment 3: Voltage Rises and Voltage Drops

XIII. Experiment 4: Shorts and Opens

XIV. Summary

XV. Unit Examination

XVI. Examination Answers

UNIT 3 RESISTANCE

I. Introduction
II. Unit Objectives
III. Unit Activity Guide
IV. Basic Concepts
    A. The Ohm
    B. Resistivity
    C. Conductance
    D. Factors That Determine Resistance
    E. Resistance of Wire
V. Resistors
    A. Wire-Wound Resistors
    B. Carbon-Composition Resistors
    C. Deposited-Film Resistors
    D. Resistor Ratings
        1. Resistance
        2. Tolerance
        3. Wattage
    E. Chip Resistors
F. Variable Resistors
VI. Connecting Resistors
    A. Resistors in Series
    B. Resistors in Parallel
    C. Equal Resistors in Parallel
    D. Series-Parallel Connections
VII. Experiment 5: Resistor Color Code
VIII. Experiment 6: Using the Ohmmeter
IX. Experiment 7: Measuring Resistance Characteristics
X. Experiment 8: Light Dependent Resistor
XI. Summary
XII. Unit Examination
XIII. Examination Answers

UNIT 4 OHM'S LAW

- I. Introduction
- II. Unit Objectives
- III. Unit Activity Guide
- IV. Ohm's Law
  - A. Determining Current
  - B. Finding Voltage
  - C. Finding Resistance
  - D. Summary
- V. Power
  - A. Work and Power
  - B. Power, Current, and Voltage
  - C. Power Dissipation in Resistors
  - D. Deriving More Equations
- VI. Experiment 9: Measuring Current
- VII. Experiment 10: Verifying Ohm's Law
- VIII. Experiment 11: Power
- IX. Experiment 12: Maximum Power Transfer Theorem
- X. Summary
- XI. Unit Examination
- XII. Examination Answers

UNIT 5 MAGNETISM

- I. Introduction
- II. Unit Objectives
- III. Unit Activity Guide
- IV. The Magnetic Field
  - A. Magnets
  - B. Lines of Force
  - C. Magnetic Materials
  - D. Theory of Magnetism
- V. Electricity and Magnetism
  - A. Current Flow and Magnetism
  - B. The Electromagnet
  - C. Magnetic Quantities
    - 1. Flux
    - 2. Flux Density
    - 3. Magnetomotive Force
    - 4. Field Intensity or Magnetizing Force
    - 5. Permeability
    - 6. Reluctance
  - D. Ohm's Law for Magnetic Quantities
  - E. Comparison of Units

VI. Induction
  A. Magnetic Induction
  B. Electromagnetic Induction
  C. The AC Generator
  D. The DC Generator
VII. Magnetic and Electromagnetic Applications
  A. Relay
  B. Reed Switch and Relay
  C. Record Pickup
  D. Loudspeaker
  E. Magnetic Tape
  F. DC Motor
  G. Meter
  H. Computer Memories
  I. Magnetic Deflection of Electronic Beams
VIII. Experiment 13: Electromagnetism
IX. Experiment 14: Magnetic and Electromagnetic Devices
X. Summary
XI. Unit Examination
XII. Examination Answers

UNIT 6 ELECTRICAL MEASUREMENTS
I. Introduction
II. Unit Objectives
III. Unit Activity Guide
IV. The Meter Movement
  A. Construction
  B. Operation
  C. Taut-Band Movement
V. The Ammeter
  A. Measuring Current
  B. Increasing the Range of the Ammeter
  C. Computing the Shunt Resistance
  D. Ammeter Accuracy
VI. The Voltmeter
  A. Extending the Range
  B. Calculating the Multiplier
  C. Multiple-Range Voltmeters
  D. Sensitivity (Ohms-per-volt)
  E. Loading Effect of Voltmeters

VII. The Ohmmeter
  A. Basic Circuit
  B. Scale Calibration
  C. Creating Higher Ranges
  D. Creating Lower Ranges
  E. Shunt Ohmmeter
VIII. Multimeters
  A. Basic Circuit
  B. Electronic Multimeter
  C. Measurement Inaccuracies
IX. Experiment 15: Determining the Sensitivity of Your Voltmeter
X. Experiment 16: Loading Effects of the Voltmeter
XI. Summary
XII. Unit Examination
XIII. Examination Answers

UNIT 7 DC CIRCUITS
I. Introduction
II. Unit Objectives
III. Unit Activity Guide
IV. Simple Circuits
  A. Series Circuit
  B. Parallel Circuit
  C. Series-Parallel Circuit
V. Voltage Dividers
VI. Bridge Circuits
  A. Balanced Bridge
  B. Unbalanced Bridge
  C. Wheatstone Bridge
  D. Self-Balancing Bridge
  E. Temperature Sensing Bridge
VII. Experiment 17: Bridge Circuits
VIII. Kirchhoff's Law
  A. Kirchhoff's Voltage Law
  B. How to Use Kirchhoff's Law
  C. Kirchhoff's Current Law
IX. Superposition Theorem
X. Thevenin's Theorem
XI. Norton's Theorem
  A. Current Sources and Voltage Sources
  B. Finding the Norton Equivalent
  C. Norton-Thevenin Conversions
XII. Experiment 18: Network Theorems
XIII. Summary
XIV. Unit Examination
XV. Examination Answers

UNIT 8 INDUCTION AND CAPACITANCE
- I. Introduction
- II. Unit Objectives
- III. Unit Activity Guide
- IV. Inductance
  - A. Self-Induction
  - B. Inductance
  - C. Inductors
  - D. Time Constant of an Inductor
  - E. Inductors in Combination
    - 1. Inductors in Series
    - 2. Inductors in Parallel
    - 3. Inductors in Series-Parallel
- V. Capacitance
  - A. Capacitors
  - B. Charging the Capacitor
  - C. Discharging the Capacitor
- VI. Capacitors
  - A. Unit of Capacitance
  - B. Factors Determining Capacitance
  - C. Types of Capacitors
    - 1. Variable Capacitors
    - 2. Fixed Capacitors
- VII. RC Time Constants
- VIII. Experiment 19: RC Time Constants
- IX. Capacitors in Combination
  - A. Capacitors in Parallel
  - B. Capacitors in Series
- X. Experiment 20: Series and Parallel Capacitors
- XI. Experiment 21: Using Capacitors
- XII. Summary
- XIII. Unit Examination
- XIV. Examination Answers

APPENDIX A SCIENTIFIC NOTATION

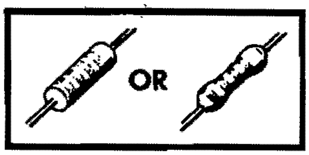
PARTS LIST

This parts list contains all of the parts used in the experiments which you will perform with this course. The key numbers in the parts list correspond to the numbers in the parts illustrations. Some parts are packaged in envelopes. Except for this initial parts check, keep these parts in their envelopes until they are called for in an experiment.

RESISTORS

KEY No.	PART No.	QTY.	DESCRIPTION
A1	6-106	1	10 MΩ, 1/2-watt, 5% (brown-black-blue-gold)
A1	6-101	2	100 Ω, 1/2-watt, 5% (brown-black-brown-gold)
A1	6-102	2	1000 Ω, 1/2-watt, 5% (brown-black-red-gold)
A1	6-103	1	10 kΩ, 1/2-watt, 5% (brown-black-orange-gold)
A1	6-105	1	1 MΩ, 1/2-watt, 5% (brown-black-green-gold)
A1	6-122	1	1200 Ω, 1/2-watt, 5% (brown-red-red-gold)
A1	6-201	1	200 Ω, 1/2-watt, 5% (red-black-brown-gold)
A1	6-202	1	2000 Ω, 1 /2-watt, 5% (red-black-red-gold)
A1	6-223	1	22 kΩ, 1/2-watt, 5% (red-red-orange-gold)
A1	6-471	1	470 Ω, 1/2-watt, 5% (yellow-violet-brown-gold)
A1	6-680	1	68 Ω, 1/2-watt, 5% (blue-gray-black-gold)
A1	6-683	1	68 kΩ, 1/2-watt, 5% (blue-gray-orange-gold)

A1



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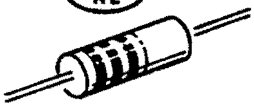
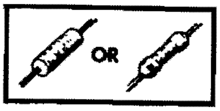


NOTE: The following resistors are in the envelope labeled: RESISTORS FOR EXPERIMENT 5 or R For Exp 5. Return these parts to the envelope after you have checked them.

A1	6-106	1	10 MΩ, 1/2-watt, 5% (brown-black-blue-gold)
A1	6-105	1	1 MΩ, 1/2-watt, 5% (brown-black-green)
A2	6-100-1	1	10 Ω, 1-watt, 5% (brown-black-black-gold)
A4	6-101-2	1	100 Ω, 2-watt, 5% (brown-black-brown-gold)
A2	6-102-1	1	1000 Ω, 1-watt, 5% (brown-black-red-gold)
A1	6-103	1	10 kΩ, 1/2-watt, 5% (brown-black-orange-gold)
A1	6-150	1	15 Ω, 1/2-watt, 5% (brown-green-black-gold)
A3	6-153-12	1	15 kΩ, 1/4-watt, 5% (brown-green-orange-gold)
A1	6-220	1	22 Ω, 1/2-watt, 5% (red-red-black-gold)
A4	6-221-2	1	220 Ω, 2-watt, 5% (red-red-brown-gold)
A1	6-222	1	2200 Ω, 1/2-watt, 5% (red-red-red-gold)
A3	6-222-12	1	2200 Ω, 1/4-watt, 5% (red-red-red-gold)
A1	6-224	1	220 kΩ, 1/2-watt, 5% (red-red-yellow-gold)
A1	6-333	1	33 kΩ, 1/2-watt, 5% (orange-orange-orange-gold)
A2	6-471-1	1	470 Ω, 1-watt, 5% (yellow-violet-brown-gold)
A1	6-472	1	4700 Ω, 1/2-watt, 5% (yellow-violet-red-gold)
A3	6-472-12	1	4700 Ω, 1/4-watt, 5% (yellow-violet-red-gold)
A1	6-479	1	4.7 Ω, 1/2-watt, 5% (yellow-violet-gold-gold)
A1	6-512	1	5100 Ω, 1/2-watt, 5% (green-brown-red-gold)
A3	6-561-12	1	560 Ω, 1/4-watt, 5% (green-blue-brown-gold)

A3



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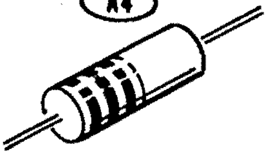

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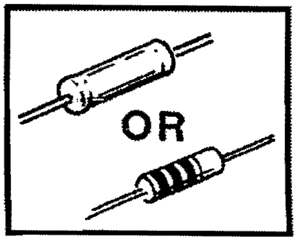
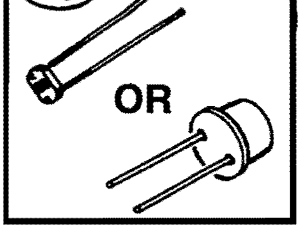


RESISTORS (precision)

A5	6-1001	1	1000 Ω, 1/2-watt, 1% (brown-black-black-brown-brown)
A5	6-1009	1	10 Ω, 1/2-watt, 1% (brown-black-black-gold-brown)
A5	6-1000	1	100 Ω, 1/2-watt, 1% (brown-black-black-black-brown)

KEY No.	PART No.	QTY.	DESCRIPTION
RESISTORS (special purpose)			
A6	9-83	1	Light-dependent resistor
A7	9-182	1	Thermistor (100 kΩ)
A8	9-34	1	Thermistor (120 Ω)
CONTROLS-SWITCHES-RELAYS			
A9	10-917	1	200 Ω linear control
A10	60-2	1	Slide switch (DPDT)
A11	65-24	1	Magnetic reed switch (SPST)
A12	69-136	1	Relay
CAPACITORS (electrolytic)			
A13	25-880	1	10 µF, 35V
A14	25-883	1	47 µF, 35V
A15	25-960	1	470 µF, 35V
MISCELLANEOUS			
	331-7	1	Solder package
	340-18	1	1 foot of Nichrome wire
	344-59	1	10 feet of #22 solid wire
A16	406-4	1	Compass
A17	412-16	1	#49 light bulb
A18	421-50	1	1/16 amp fuse
A19	434-21	1	Light socket
A20	474-1	1	Permanent magnet
	266-962	1	Small parts container

A6



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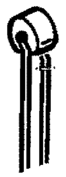

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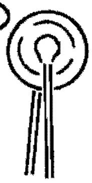

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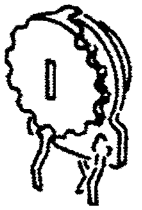

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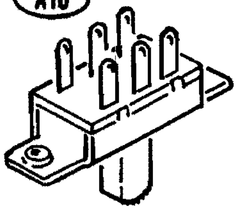

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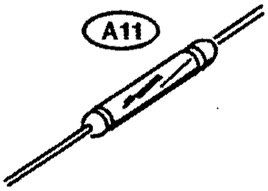

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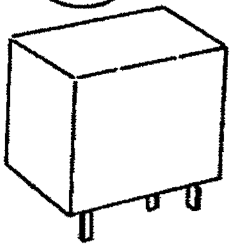

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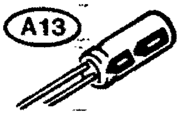

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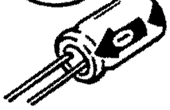

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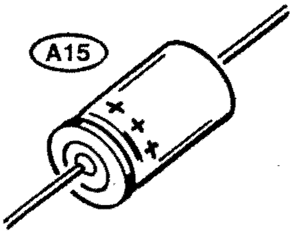

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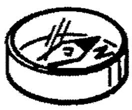

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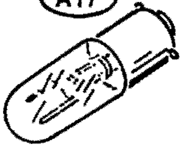

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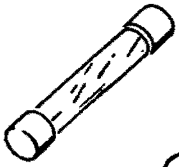

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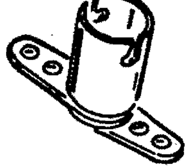
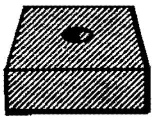
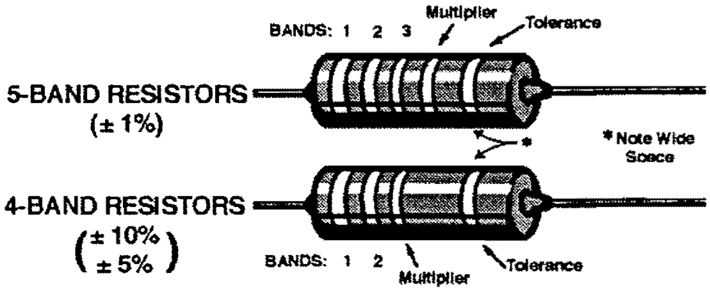


A20



The 1% resistor supplied with this course may be one of two possible styles: The value will either be printed on the body, or it will be identified by a 5-band color code. This color code is the same as the familiar 4-band system except the third band provides an extra digit of resolution. A comparative example is shown below.


BANDS: 1 2 3
Multiplier
Tolerance
5-BAND RESISTORS (± 1%)
* Note Wide Space
4-BAND RESISTORS (± 10% ± 5%)
BANDS: 1 2
Multiplier
Tolerance

Resistance Tolerance

Color	Tolerance
Silver	± 10%
Gold	± 5%
Brown	± 1%
Green	± .5%

UNIT 1

CURRENT

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INTRODUCTION

Electronics is the science which explains the behavior of *electrons* to perform some useful function. As this definition implies, the electron is vitally important to electronics. In fact, the word *electronics* is derived from the word *electron.* Electricity comes to our homes and offices by the movement of electrons through wires. Actually, electric current is nothing more than the movement of electrons. Obviously then, to understand electronics, you must first understand the nature of the electron. In this unit, you will see what the electron is, how it behaves, and how you can use it to perform useful jobs. You will also learn how to measure the flow of electrons.

The unit objectives state exactly what you are expected to learn from this unit. Study this list now and refer to it often as you study the text. The unit activity guide follows the unit objectives. It lists the order in which you should complete this unit. You should check off each activity as you complete it.

UNIT OBJECTIVES

When you complete this unit, you will be able to:

1. Define the following terms: Direct current (dc), alternating current (ac), molecule, element, atom, proton, neutron, electron, nucleus, ion, coulomb, ampere, conductor, insulator, valence, current, directed drift, battery, and polarity.

2. State Coulomb's Law and the effects of the behavior of like and unlike charges.

3. State the electrical charge that is associated with the following: Atom, electron, proton, neutron, nucleus, and ion.

4. Given a simple diagram of Bohr's atomic model, identify the three basic atomic particles.

5. Name the three basic parts of an electrical circuit.

6. Given a simple circuit schematic diagram, indicate the direction of current flow.

7. Draw a schematic of a circuit using the resistor, battery, and conductor schematic symbols.

8. State the correct method for connecting an ammeter into a circuit.

UNIT ACTIVITY GUIDE

	Completion Time
☐ Read "Composition of Matter."	
☐ Complete Programmed Review Frames 1-14.	
☐ Read "Electrostatics."	
☐ Complete Programmed Review Frames 15-30.	
☐ Read "Current Flow."	
☐ Complete Programmed Review Frames 31-42.	
☐ Read "The Electric Circuit."	
☐ Complete Programmed Review Frames 43-50.	
☐ Read "Measuring Current."	
☐ Complete Programmed Review Frames 51-57.	
☐ Perform Experiment 1.	
☐ Study Summary.	
☐ Complete Unit Examination.	
☐ Check Examination Answers.	

COMPOSITION OF MATTER

Controlling the behavior of electrons is what electronics is all about. Therefore, an understanding of the electron is vitally important to an understanding of electronic fundamentals. *Electrons* are tiny particles which carry the energy to light our homes, cook our food, and do much of our work. To understand what an electron is, we must investigate the makeup of matter.

Matter is generally described as anything which has weight and occupies space. Thus, the earth and everything on it is classified as matter. Matter exists in three different states—solid, liquid, and gas. Examples of solid matter are gold, sand, and wood. Some liquid examples are water, milk, and gasoline. Helium, hydrogen, and oxygen, are examples of gas forms of matter.

Elements and Compounds

The basic building materials from which all matter is constructed are called *elements*. Hence, all matter is comprised of elements. Some examples of elements are iron, carbon, hydrogen, and gold. Just over one hundred elements are presently known. Of these, only 92 occur in nature. These are called natural elements. Figure 1-1A lists the names of the 92 natural elements. In addition, there are about a dozen man-made elements. These are shown in Figure 1-1B.

As we look around us, it becomes obvious that there are many more types of matter than there are elements. For example, substances like salt, steel, water, and protein do not appear in the list of elements. The reason for this is that these substances are not elements. Instead, they are called *compounds*. A compound is a substance which is composed of two or more elements. Just as the letters of the alphabet can be arranged in various combinations to form millions of different words, the elements can be arranged in various combinations to form millions of different compounds. For example, water is a compound which is made up of the elements hydrogen and oxygen. On the other hand, sugar is comprised of hydrogen, carbon, and oxygen while salt is comprised of sodium and chlorine.

To better understand how the compound is related to its elements, let's investigate the structure of a compound with which we are all familiar — water. Suppose we divide a drop of water into two parts. Next, suppose we divide each part again and again. After a few dozen divisions, we have a drop so small that it can be seen only with a microscope. If we could divide it even further into smaller and smaller particles, we would eventually get a particle so small that it could not be divided further and *still be water*. The smallest particle of water which still retains the characteristics of water is called a *molecule*. The water molecule can be broken into still smaller pieces, but the pieces will not be water. Thus, if we break up the water molecule, we find that the pieces are the elements hydrogen and oxygen.

THE NATURAL ELEMENTS

A

Atomic Number	Name	Symbol	Atomic Number	Name	Symbol	Atomic Number	Name	Symbol
1	Hydrogen	H	32	Germanium	Ge	63	Europium	Eu
2	Helium	He	33	Arsenic	As	64	Gadolinium	Gd
3	Lithium	Li	34	Selenium	Se	65	Terbium	Tb
4	Beryllium	Be	35	Bromine	Br	66	Dysprosium	Dy
5	Boron	B	36	Krypton	Kr	67	Holmium	Ho
6	Carbon	C	37	Rubidium	Rb	68	Erbium	Er
7	Nitrogen	N	38	Strontium	Sr	69	Thulium	Tm
8	Oxygen	O	39	Yttrium	Y	70	Ytterbiura	Tb
9	Fluorine	F	40	Zirconium	Zr	71	Lutetium	Lu
10	Neon	Ne	41	Niobium	Nb	72	Hafnium	Hf
11	Sodium	Na	42	Molybdenum	Mo	73	Tantalum	Ta
12	Magnesium	Mg	43	Technetium	Tc	74	Tungsten	W
13	Aluminum	Al	44	Ruthenium	Ru	75	Rhenium	Re
14	Silicon	Si	45	Rhodium	Rh	76	Osmium	Os
15	Phosphorus	P	46	Palladium	Pd	77	Iridium	Ir
16	Sulfur	S	47	Silver	Ag	78	Platinum	Pt
17	Chlorine	Cl	48	Cadmium	Cd	79	Gold	Au
18	Argon	A	49	Indium	In	80	Mercury	Hg
19	Potassium	K	50	Tin	Sn	81	Thallium	Tl
20	Calcium	Ca	51	Antimony	Sb	82	Lead	Pb
21	Scandium	Sc	52	Tellurium	Te	83	Bismuth	Bi
22	Titanium	Ti	53	Iodine	I	84	Polonium	Po
23	Vanadium	V	54	Xenon	Xe	85	Astatine	At
24	Chromium	Cr	55	Cesium	Cs	86	Radon	Ra
25	Manganese	Mn	56	Barium	Ba	87	Francium	Fr
20	Iron	Fe	57	Lanthanum	La	88	Radium	Ra
27	Cobalt	Co	58	Cerium	Ce	89	Actinium	Ac
28	Nickel	Ni	59	Praseodymium	Pr	90	Thorium	Th
29	Copper	Cu	60	Neodymium	Nd	91	Protactinium	Pa
30	Zinc	Zn	61	Promethium	Pm	92	Uranium	U
31	Gallium	Ga	62	Samarium	Sm			

THE ARTIFICIAL ELEMENTS

B

Atomic Number	Name	Symbol	Atomic Number	Name	Symbol	Atomic Number	Name	Symbol
93	Neptunium	Np	97	Berkelium	Bk	101	Mendelevium	Mv
94	Plutonium	Pu	98	Californium	Cf	102	Nabelium	Na
95	Americum	Am	99	Einsteinium	Es	103	Lawrencium	Lr
96	Curium	Cm	100	Fermium	Fm	104	Rutherfordium	Rf

Figure 1-1

Table of elements.

Atoms

The smallest particle to which an *element* can be reduced is called an *atom*. Molecules are made up of atoms which are bound together. The water molecule is shown in Figure 1-2 as three atoms. The two smaller atoms represent hydrogen while the large one represents oxygen. Therefore, a molecule of water consists of two atoms of hydrogen (H) and one atom of oxygen (O). This is why the chemical formula for water is H_2O.

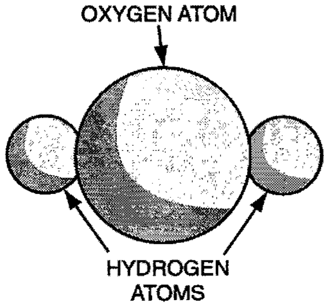


Figure 1-2

The water molecule.

Electrons, Protons, and Neutrons

As small as the atom is, it can be broken up into even smaller particles. If we investigate the structure of the atom, we find that it is comprised of three elementary particles. These particles are called *electrons*, *protons*, and *neutrons*. These are the three basic building blocks which make up all atoms and, therefore, all matter. Electrons, protons, and neutrons have very different characteristics. However, as far as is known, all electrons are exactly alike. By the same token, all protons are exactly alike. And finally, all neutrons are exactly alike.

Bohr Model of an Atom

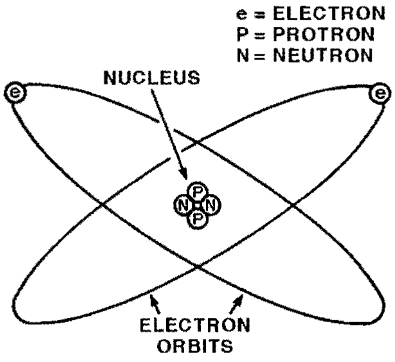


Figure 1-3
Bohr model of the helium atom.

Figure 1-3 shows how electrons, protons, and neutrons are combined to form an atom. This particular one is a helium atom. Two protons and two neutrons are bunched together near the center of the atom. The center part of the atom which is comprised of protons and neutrons is called the nucleus. Depending upon the type of atom, the nucleus will contain from one to about 100 protons. Also, in all atoms except hydrogen, the nucleus contains neutrons. The neutrons and protons have approximately the same weight and size. The overall weight of an atom is determined primarily by the number of protons and neutrons in the nucleus.

Rotating around the nucleus are the electrons. Notice that the helium atom has two electrons. The electrons are extremely light and travel at fantastic speeds. The atom can be compared to the solar system with the nucleus representing the sun and the electrons representing the planets. The electrons orbit the nucleus in much the same way that the planets orbit the sun.

It is interesting to note that no one has ever seen an atom because of its small size. Thus, any picture of the atom must be based upon assumptions rather than actual observation. Figure 1-3 represents a very simple picture of the atom based upon these assumptions. Today, much more complex models of the atom have been proposed. However, all of these models have several things in common. They all assume that the basic structure is that of electrons orbiting about a nucleus which is comprised largely of protons and neutrons. Thus, the model shown in Figure 1-3 is adequate for our purposes, even though it may be somewhat simplified. This model of the atom is called the Bohr model after the man who proposed it.

Difference Between Elements

At present there are 104 known elements, although only 92 of these commonly occur in nature. The difference between these elements is their atomic structure. That is, each is made up of atoms which contain a unique number of protons, electrons, and, with the exception of hydrogen, neutrons. Let's look at Figure 1-4 to see exactly what we mean.

The simplest of all elements, hydrogen, is shown in Figure 1-4A. It consists of a single electron orbiting a single proton. This is the only atom that does not contain a neutron. Because it is made up of the fewest number of particles, hydrogen is the lightest element.

Figure 1-4B is a representation of the carbon atom. Notice, this atom is made up of 6 electrons which orbit a nucleus of 6 protons and 6 neutrons.

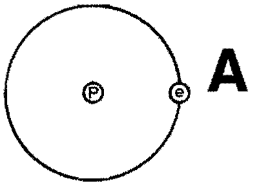
The heaviest element depicted in Figure 1-4 is copper. It consists of 29 electrons, 29 protons, and 35 neutrons. However, the most complex atom commonly found in nature is the uranium atom. It has 92 electrons, 92 protons and 146 neutrons.

The Balanced Atom

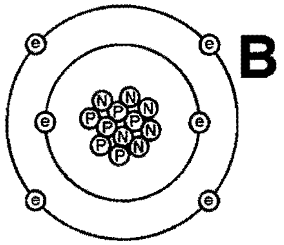
In the examples shown, you may have noticed that the number of electrons is always equal to the number of protons. This is normally true of any atom. When this is the case, the atom is said to be in its *normal*, *balanced*, or *neutral* state. As we will see later, this state can be upset by an external force. However, we normally think of the atom as containing equal numbers of electrons and protons.

Programmed Review

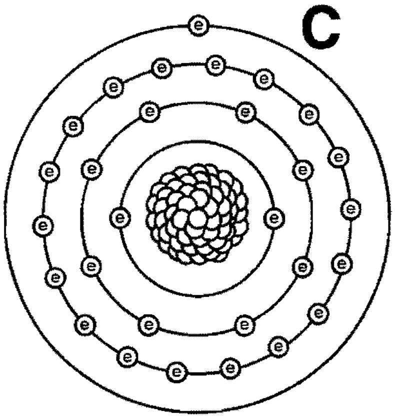
All reviews in this course are presented in a programmed instruction (P.I.) format. They test your knowledge and enhance your understanding of the material presented in this section. Read each of the number of electrons, protons, numbered frames carefully and fill in the missing blanks at the bottom of each frame. The correct answers appear in parentheses at the beginning of the next frame. Use a sheet of paper to cover all of the frames below the one you are reading.



HYDROGEN ATOM
(one electron, one protron)



CARBON ATOM
(6 electrons, 6 protrons, 6 neutrons)



COPPER
(29 electrons, 29 protrons, 35 neutrons)

Figure 1-4
The difference between atoms is the number of electrons, protrons, and neutrons that they have.

1. Matter is anything which has weight and occupies space. Thus, air, metal, and water are examples of _______________ .

2. (matter) Matter may exist as a gas, liquid, or solid. All matter is comprised of one or more of the elements. For example, water is comprised of two _______________ called hydrogen and oxygen.

3. (elements) A substance which is comprised of two or more elements is called a compound. Since water is comprised of the elements hydrogen and oxygen, water is a _______________ .

4. (compound) Other examples of compounds are salt, steel, and sugar. All of these substances are compounds because they are comprised of two or more _______________ .

5. (elements) All of the compounds found in nature consist of different combinations of only 92 different elements. These basic elements can be combined in millions of different combinations to form all of the _______________ known to man.

6. (compounds) The smallest particle of a compound is called a molecule. A molecule is comprised of atoms of two or more different elements. For example, a molecule of water consists of two atoms of hydrogen and one atom of oxygen. Thus, the smallest particle of water which is still water is a _______________ .

7. (molecule) A molecule consists of two or more atoms bound together. Thus, while the molecule is the smallest particle of a compound, the atom is the smallest particle of an _______________ .

8. (element) Just as a compound is made up of molecules, an element is made up of ______________ .

9. (atoms) The atom is the smallest particle into which an element can be divided. Since there are only 92 natural elements there are only 92 different types of ______________ found in nature.

10. (atoms) One type of atom differs from another type by the number of protons, electrons, and neutrons which it contains. These are the three basic building blocks from which all atoms are made. That is, all atoms are made up of different combinations of ______________, ______________, and ______________ .

11. (protons, electrons, neutrons) The protons and neutrons form the center or nucleus of the atom. The electrons rotate around the nucleus in much the same way that the planets rotate around the sun. Thus, if we compare the atom to our solar system, the sun is equivalent to the ______________ of the atom.

12. (nucleus) The nucleus of the hydrogen atom consists of a single proton. However, all other atoms have both protons and ______________ in their nucleus.

13. (neutrons) It is interesting to note that atoms normally have the same number of electrons and protons. Thus, a hydrogen atom has one proton and one electron. On the other hand, a uranium atom has 92 protons and ________ electrons.

14. (92).

ELECTROSTATICS

Electrostatics is a branch of physics that deals with electrical charges at rest, or static electricity. On the other hand, electronics deals largely with moving electrical charges. However, before we can fully understand the action of electrical charges in motion, we must first have some basic knowledge of their behavior at rest.

The Electrical Charge

We have examined the structure of the atom and discussed some of the characteristics of the electron, proton, and neutron. However, we have not yet discussed the most important characteristic of these particles. This characteristic is their *electrical charge*. An electrical charge is a property associated with the electron and the proton. It is this electrical charge which makes the electron useful in electrical and electronic work.

The electrical charge is difficult to visualize because it is not a thing, like a molecule or an atom. Rather, it is a property which electrons and protons have that causes these particles to behave in certain predictable ways.

There are two distinct types of electrical charges. Because these two types of charges have opposite characteristics, they have been given the names *positive* and *negative*. The electrical charge associated with the *electron* has been arbitrarily given the name *negative*. On the other hand, the electrical charge associated with the *proton* is considered *positive*. The neutron has no electrical charge at all. It is electrically neutral and, therefore, plays no known role in electricity.

The electron revolves around the nucleus of the atom in much the same way that the earth orbits the sun. Let's compare this action to that of a ball which is attached to the end of a string and twirled in a circle. If the string breaks, the ball will fly off in a straight line. Thus, it is the restraining action of the string which holds the path of the ball to a circle. In the case of the earth rotating around the sun, it is the gravitational attraction of the sun which prevents the earth from flying off into space. The gravitational attraction of the sun exactly balances the centrifugal force of each planet. Thus, the planets travel in more or less circular paths around the sun.

The electron orbits around the nucleus at a fantastic speed. What force keeps the electron from flying off into space? It is not gravity because the gravitational force exerted by the nucleus is much too weak. Instead, the force at work here is caused by the charge on the electron in orbit and the charge on the proton in the nucleus. The negative charge of the electron is attracted by the positive charge of the proton. We call this force of attraction an *electrostatic force*. To explain this force, science has adopted the concept of an *electrostatic field.* Every charged particle is assumed to be surrounded by an electrostatic field which extends for a distance outside the particle itself. It is the interaction of these fields which causes the electron and proton to attract each other.

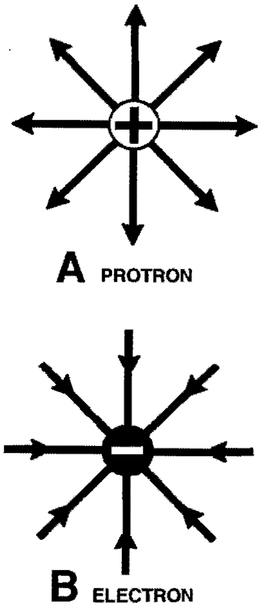


Figure 1-5
Fields associated with protrns and electrons.

Figure 1-5A shows a diagram of a proton. The plus sign represents the positive electrical charge. The arrows which extend outward represent the lines of force which make up the electrostatic field. Notice that the lines are arbitrarily assumed to extend outward away from the positive charge. Compare this to the electron shown in Figure 1-5B. The minus sign represents the negative charge while the arrows which point inward represent the lines of the electric field. Now let's see how these two fields interact with one another.

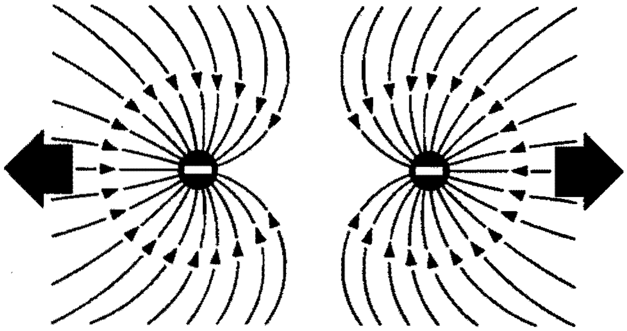
Law of Electrical Charges

There is a basic law of nature which describes the action of electrical charges. It is called Coulomb's Law after Charles A. de Coulomb who discovered this relationship.

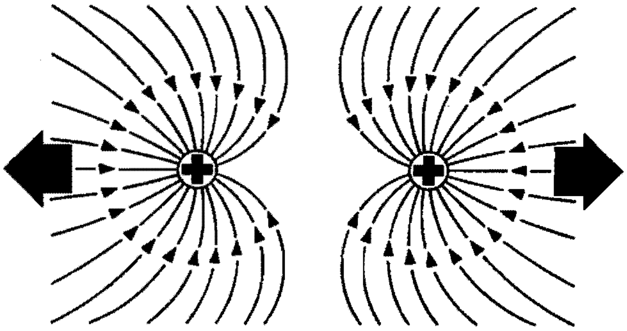
Quite simply, Coulomb's Law states that:

1. Like charges repel.
2. Unlike charges attract.

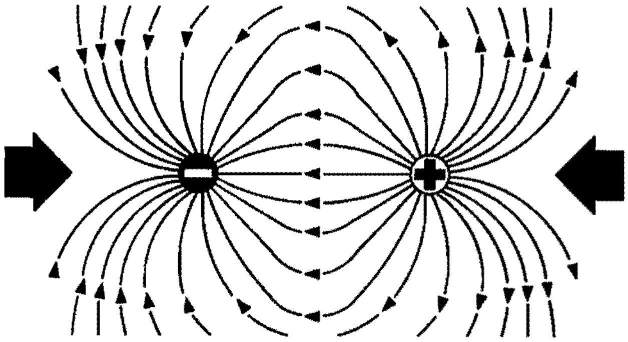
Because like charges repel, two electrons repel each other as do two protons. Figure 1-6A illustrates how the lines of force interact between two electrons. The directions of the lines of force are such that the two fields cannot interconnect. The net effect is that the electrons attempt to move apart. That is, they repel each other. Figure 1-6B illustrates that the same is true of two protons. In Figure 1-6C, an electron and a proton are shown. Here, the two fields do interconnect. As a result, the two charges attract and tend to move together.



A ELECTRONS REPEL



B PROTRONS REPEL



C ELECTRON AND PROTRON ATTRACT

Figure 1-6
Action of like and unlike charges.

These examples show only individual charged particles. However, Coulomb's Law holds true for concentrations of charges as well. In fact, it holds true for any two charged bodies. An important part of Coulomb's Law is an equation which allows us to determine the force of attraction, or repulsion, between charged bodies. The equation states that:

$$F = \frac{q_1 \times q_2}{d^2}$$

Where:

F = the force of attraction between unlike charges, or the force of repulsion between like charges
q_1 = the charge on one body
q_2 = the charge on the second body
d^2 = the square of the distance between the two bodies.

While we need not work actual problems to determine the force between charges, we can see some interesting relationships by examining the equation. If we experiment with the equation by substituting some simple arbitrary numbers for q_1, q_2, and d^2, we can determine how the force changes as the quantities change. For example, if the value of either charge doubles, the force also doubles. If both charges double, then the force increases by a factor of four. On the other hand, increasing the distance between charges decreases the force. If the distance between charges is doubled, the force is reduced to one fourth its former value.

The magnitude of the negative charge on the electron is exactly equal to the magnitude of the positive charge on the proton. Figure 1-7 is a diagram of a hydrogen atom consisting of one electron in orbit around one proton. Notice that the negative charge of the electron is exactly offset by the positive charge of the proton. Thus, the atom as a whole has no charge at all. That is, overall, this atom has neither a negative nor a positive charge. It is electrically neutral.

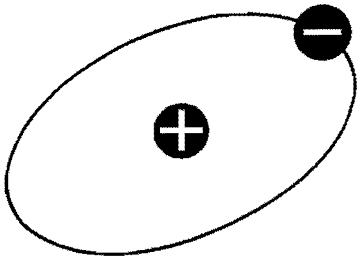


Figure 1-7
Hydrogen atom.

Atoms which are electrically neutral have no net charge. Therefore, they neither attract nor repel each other. By the same token they are neither attracted nor repelled by charged particles such as electrons and protons. We have seen that atoms normally contain the same number of electrons (negative charges) as protons (positive charges). And, since the neutrons add no charge, all atoms are normally neutral as far as their electrical charges are concerned. However, this normal condition can be easily upset by external forces.

The Ion

Atoms are affected by many outside forces such as heat, light, electrostatic fields, chemical reactions, and magnetic fields. Quite often the balanced state of the atom is upset by one or more of these forces. As a result, an atom can lose or gain an electron. When this happens, the number of negative charges is no longer exactly offset by the number of positive charges. Thus, the atom ends up with a net charge. An atom which is no longer in its neutral state is called an *ion*. The process of changing an atom to an ion is called *ionization*.

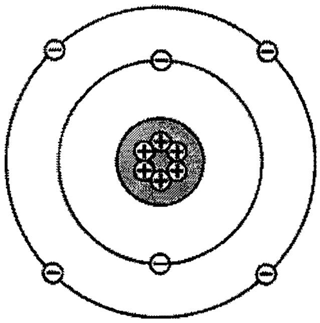
There are both negative and positive ions. Figure 1-8 compares a neutral atom of carbon with negative and positive ions of carbon. Figure 1-8A shows the balanced, or neutral, atom. Notice that the six negative charges (electrons) are exactly offset by the six positive charges (protons). The neutrons are ignored in this example since they contribute nothing to the electrical charge.

Figure 1-8B shows the condition which exists when the carbon atom loses an electron. There are many forces in nature which can dislodge an electron and cause it to wander away from the atom. We will discuss this in more detail later. Notice that the carbon atom now has one more proton than electrons. Thus, there is one positive charge which is not cancelled by a corresponding negative charge. Therefore, the atom has a net positive charge. We call this a positive ion.

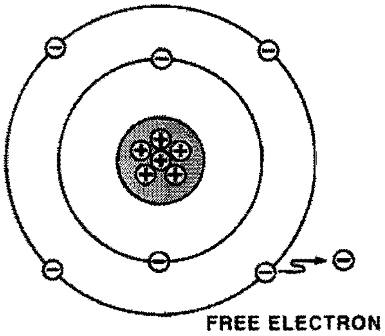
Figure 1-8C shows a carbon atom which has picked up a stray electron. In this case, there is one negative charge which is not offset by a corresponding positive charge. Hence, the atom has a net negative charge. This is called a negative ion.

The ion still has all of the basic characteristics of carbon because the nucleus of the atom has not been disturbed. Therefore, an atom can give up or pick up electrons without changing its basic characteristics.

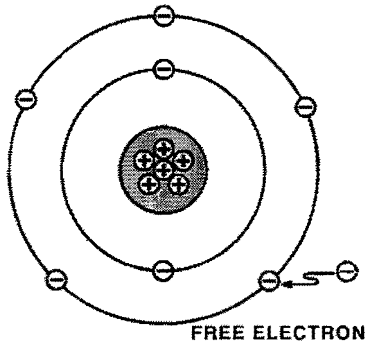
Changing atoms to ions is an easy thing to do, and everything you see around you contains ions as well as atoms. The material around you also contains a large number of free or stray electrons. These are electrons which have escaped from atoms leaving behind a positive ion. As we will see later, the electrical characteristics of different types of material are determined largely by the number of free electrons and ions within the material.



A NEUTRAL ATOM



B POSITIVE ION CAUSED BY LOSING ONE ELECTRON



C NEGATIVE ION CAUSED BY PICKING UP A STRAY ELECTRON

Figure 1-8
Carbon atom and ions.

Action of Electrostatic Charges

At one time or another we have all seen or felt the effects of electrostatic charges. A most spectacular effect which we have all seen is lightning. Less spectacular examples are often witnessed when we remove clothes from a dryer, comb our hair, or touch a metal object after scuffing our feet on a rug. In each of these cases, two different bodies receive opposite electrical charges. This is caused by one of the bodies giving up a large number of electrons to the other. The body which gives up the electrons becomes positively charged while the body receiving the electrons becomes negatively charged.

When we comb our hair vigorously with a hard rubber comb, our hair gives up electrons to the comb. Thus, the comb becomes negatively charged while our hair becomes positively charged. That is, the comb collects a large number of free electrons from our hair. This is an example of *charging by friction.*

There are several other ways in which an object can be charged. For example, the charge on the comb can be partially transferred to another body simply by touching the comb to the uncharged body. When the charged comb comes into contact with the uncharged object, many of the excess electrons leave the comb and collect on the other object. If we now remove the comb, the object will have a charge of its own. This is called *charging by contact.*

Another method of charging is called *charging by induction.* This method takes advantage of the electrostatic field which exists in the space surrounding a charged body. This allows us to charge an object without actually touching it with a charged body. Figure 1-9 shows the negatively charged comb placed close to an aluminum rod. The excess electrons in the comb repel the free electrons in the rod. Consequently, the free electrons gather at the end of the rod away from the charged comb. This causes that end of the rod to acquire a negative charge. The opposite end acquires a positive charge because of the deficiency of electrons. If we now touch the negative end of the rod with a neutral body, some of the electrons leave the rod and enter the neutral body. This leaves the rod with a net positive charge. Thus, we have induced a positive charge into the rod without touching it with a charged body.

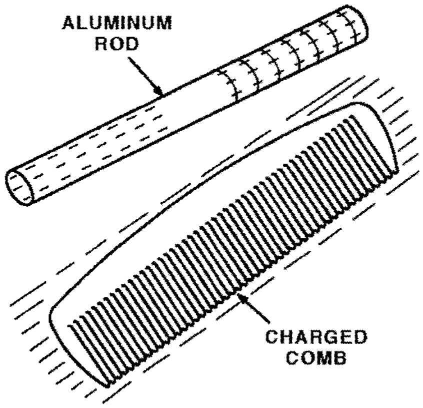


Figure 1-9
Charging by induction.

Now, let's see how electrical charges can be neutralized. When a glass rod is rubbed with a silk cloth, the glass gives up electrons to the silk. Therefore, the glass become positively charged while the silk becomes negatively charged. This is shown in Figure 1-10A. However, if the rod is now brought back into contact with the cloth, the negative electrons in the silk are attracted by the positive charge in the glass. The force of attraction pulls the electrons back out of the silk so that the charge is neutralized as shown in Figure 1-10B. Thus, if two objects having equal but opposite charges are brought into contact, electrons flow from the negatively charged object into the positively charged object. The flow of electrons continues until both charges have been neutralized.

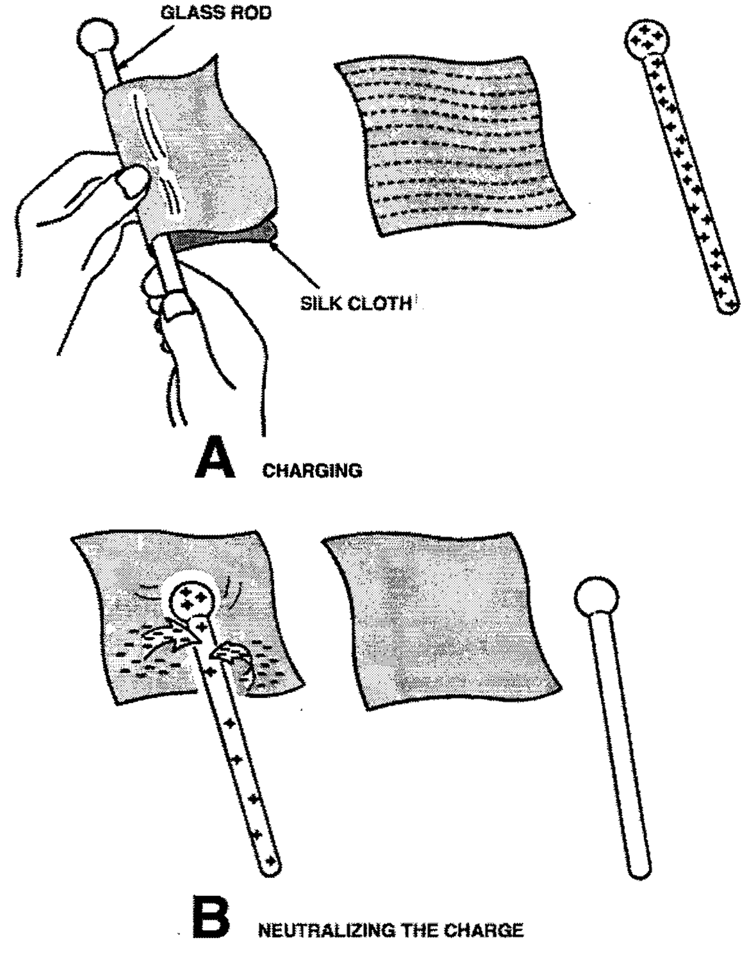


Figure 1-10
Charging and discharging a glass rod.

Programmed Review

15. Electricity is a property that electrons and protons have which causes them to behave in certain predictable ways. Each has a tiny electrical charge. However, the electron's charge is opposite to that of the proton. The proton is said to have a positive charge, while the electron has a ____________ charge.

16. (negative) Although the two charges are opposite, they have exactly the same magnitude. Thus, the positive charge on the proton has the same strength as the negative charge on the ____________ .

17. (electron) While the electron and proton have electrical charges, the third particle found in the atom does not. That is, the ____________ has no electrical charge.

18. (neutron) The negatively charged electrons are held in orbit around the nucleus by the attraction of the positively charged ____________ in the nucleus of the atom.

19. (protons) A law which describes how charged particles behave is called Coulomb's Law. The action described in Frame 18 is summarized by one part of Coulomb's Law which states that "unlike charges ____________."

20. (attract) This law goes on to say that like charges behave in the opposite manner. It states that "like charges ____________ ."

21. (repel) According to Coulomb's Law, two electrons should ____________ each other.

22. (repel) Also, any two positively charged bodies should ____________ .

23. (repel) However, a negatively charged body should be attracted by a ____________ charged body.

24. (positively) Normally an atom contains the same number of electrons as protons. Thus, the positive charges in the nucleus are exactly offset by the negative charges in orbit around the nucleus. An atom has no net charge when it has the same number of protons as ______________ .

25. (electrons) An atom which has a net electrical charge is called an ion. Ions are formed when an atom loses one or more electrons, or picks up one or more extra electrons. Since electrons have *negative charges,* an atom which picks up an extra electron becomes a ______________ ion.

26. (negative) On the other hand, an atom; which loses an electron becomes a ______________ ion.

27. (positive) One way to produce free electrons and positive ions, is to rub a glass rod with a silk cloth. The glass rod gives up many electrons to the silk cloth. Thus, the glass rod becomes ______________ charged.

28. (positively) Simultaneously, the silk cloth becomes ____________ charged.

29. (negatively) Once the glass rod is positively charged, this charge can be partially transferred to a neutral body by touching the two objects together. When the two objects touch, electrons are drawn from the neutral body by the positive charge on the rod. Thus, the charge on the rod is partially neutralized. However, because the neutral body gave up electrons, it now has a ________________ charge.

30. (positive) This is called charging by contact. Objects can also be charged by induction without actually touching.

CURRENT FLOW

In electronics, *current is* defined as the flow of electrical charge from one point to another. We have already seen some examples of this. We saw that when a negatively charged body is touched to a positively charged body, electrons flow from the negative object to the positive object. Since electrons carry a negative charge, this is an example of electrical charges flowing. Before an electron can flow from one point to another, it must first be freed from the atom. Therefore, let's take a closer look at the mechanism by which electrons are dislodged from the atom.

Freeing Electrons

We have seen that electrons revolve around the nucleus at very high speeds. Two forces hold the electron in a precarious balance. The centrifugal force of the electron is exactly offset by the attraction of the nucleus. This balanced condition can be upset very easily so that the electron is dislodged.

Not all electrons can be freed from the atom with the same ease. Some are dislodged more easily than others. To see why, we must discuss the concept of *orbital shells.* Scientists believe that the orbits of the electrons in an atom fall in a certain pattern. For example, in all atoms which have two or more electrons, two of the electrons orbit relatively close to the nucleus. The area in which these electrons rotate is called a *shell.* The shell closest to the nucleus contains two electrons. This area can support only two electrons and all other electrons must orbit in shells further from the nucleus.

A second shell somewhat further from the nucleus can contain up to eight electrons. There is also a third shell which can contain up to 18 electrons and a fourth shell which can hold up to 32 electrons. The first four shells are illustrated in Figure 1-11. Although not shown, there are also additional shells in the heavier atoms.

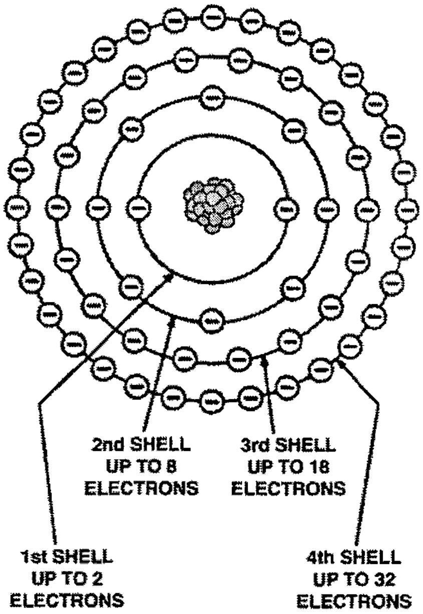

2nd SHELL UP TO 8 ELECTRONS
3rd SHELL UP TO 18 ELECTRONS
1st SHELL UP TO 2 ELECTRONS
4th SHELL UP TO 32 ELECTRONS

Figure 1-11
Arrangement of orbital shells in an atom.

Of particular importance to electronics is the outer electron shell of the atom. Hydrogen and helium atoms have one and two electrons respectively. In this case, the outer shell is the first (and only) shell. With atoms which have three to ten electrons, the outer shell is the second shell. Regardless of which shell it happens to be, the outer shell is called the *valence shell.* Electrons in this shell are called *valence electrons.*

Electrons are arranged in such a way that the valence shell never has more than eight electrons. This may be confusing since we have seen that the third shell can contain up to 18 electrons. An example shows why both statements are true. An atom of argon contains 18 electrons—2 in the first shell, 8 in the second shell, and 8 in the third shell. It might seem that the next heavier element, potassium, would have 9 electrons in its third shell. However, this would violate the valence rule stated above. Actually, what happens is that the extra electron is placed in a fourth shell. Thus the 19 electrons are distributed in this manner—2 in the first shell, 8 in the second shell, 8 in the third shell, and 1 in the fourth shell. Notice that the outer, or valence, shell becomes the fourth shell rather than the third, since the fourth shell is established as the valence shell, the third shell can fill to its full capacity of 18 electrons.

The valence electrons are extremely important in electronics. These are the electrons which can be easily freed to perform useful functions. To see why the valence electrons are more easily freed, let's consider the structure of an atom of copper. Figure 1-12A. shows how the electrons are distributed in the various shells. Notice that the valence shell contains only one electron. This electron is further from the nucleus than any of the other electrons. From Coulomb's Law we know that the force of attraction between charged particles decreases as the distance increases. Therefore the valence electrons experience less attraction from the nucleus. For this reason, these electrons can be easily dislodged from the atom.

Since we are concerned primarily with the valence electrons, we need not show the inner electrons. Instead, we can show the atom in the simplified form shown in Figure 1-12B. Figures 1-12C and D use this simplified form to illustrate one way in which a valence electron can be freed. Here two copper atoms are shown as they might appear in a copper wire. Each valence electron is held in orbit by the attraction of the nucleus. However, the force of attraction is quite weak because the orbits are so far from the nucleus. If these two atoms are close together, the valence shells may be closer together than either electron is to its nucleus. At certain points in their orbits the two electrons may come very close together. When this happens the force of repulsion between the two electrons is stronger than the force of attraction exerted by the nucleus. Thus, one or both of the electrons may be forced out of orbit to wander as a free electron. Notice that when the electron leaves, the atom becomes a positive ion.

As the free electron wanders around through the atomic structure, it may be eventually captured by another positive ion. Or, it may come close enough to other valence electrons to force them from orbit. The point is that events like these occur frequently in many types of material. Thus, in a piece of copper wire containing billions and billions of atoms, there are bound to be billions of free electrons wandering around the atomic structure.

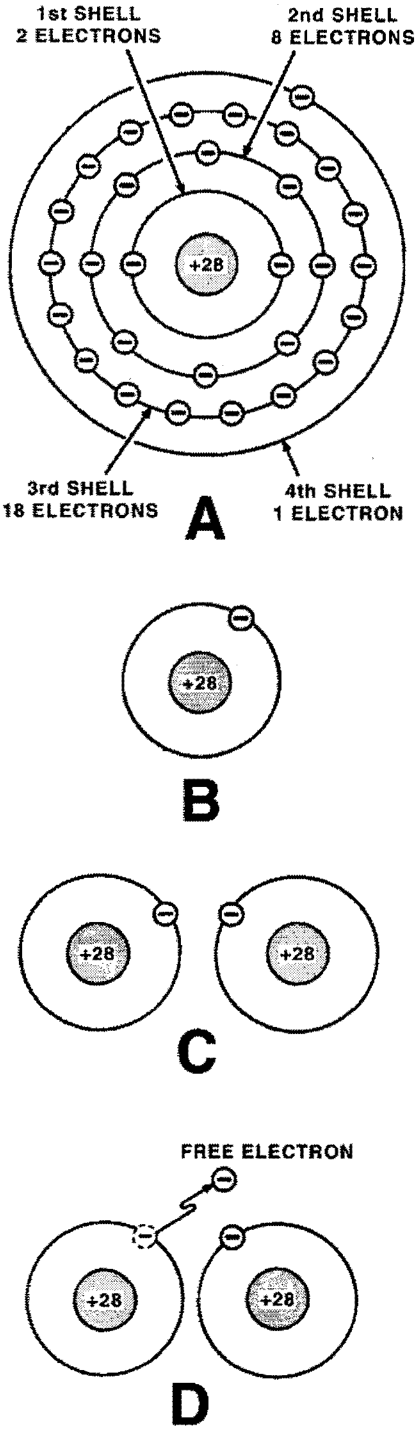


Figure 1-12
Freeing an electron from a copper atom.

Conductors and Insulators

The importance of the valence electrons cannot be emphasized too strongly. Both the electrical and the chemical characteristics of the elements depend upon the action of the valence electrons. An element's electrical and chemical stability are determined largely by the number of electrons in the valence shell. We have seen that the valence shell can contain up to eight electrons. Those elements which have valence shells that are filled or nearly filled tend to be stable. For example, the elements neon, argon, krypton, xenon, and radon have 8 electrons in their valence shell. Thus, the valence shell is completely filled. As a result, these elements are so stable that they resist any sort of chemical activity. They will not even combine with other elements to form compounds. Also, atoms of these elements are very reluctant to give up electrons. All these elements have similar characteristics in that they are all inert gases.

Elements which have their valence shells *almost* filled tend to be stable also, although they are not as stable as those whose valence shell is completely filled. These elements will strive to fill their valence shell by capturing free electrons. Consequently, elements of this type have very few free electrons wandering around through the atomic structure. Substances which have very few free electrons are called *insulators*. In addition to certain elements which act as insulators, there are many compounds which have few free electrons. Thus, they act as insulators also. By opposing the production of free electrons, these substances resist certain electrical actions. Insulators are important in electrical and electronics work for this reason. The plastic material on electrical wires is an insulator which protects us from electrical shock.

Elements in which the valence shell is almost empty have the opposite characteristics. Those which have only one or two electrons tend to give up these electrons very easily. For example, copper, silver, and gold each have one valence electron. In these elements, the valence electrons are very easily dislodged. Consequently, a bar of any one of these elements will have a very large number of free electrons. Substances which have a large number of free electrons are called *conductors*. In addition to silver, copper, and gold, some other good conductors are iron, nickel, and aluminum. Notice that all of these elements are metals. Most metals are good conductors. Conductors are important because they are used to carry electrical current from one place to another.

In some elements, the valence shell is half filled. That is, there are four valence electrons. Two examples of elements of this type are silicon and germanium. We call these elements *semiconductors* because they are neither good conductors nor good insulators. Semiconductors are important in electronics because transistors and integrated circuits are comprised of these elements. However, in this course, we are concerned primarily with conductors and insulators.

The Battery

Current flow is the movement of free electrons from one place to another. Thus, to have current flow we must first have free electrons. We have seen how valence electrons can be dislodged from atoms to form free electrons and positive ions. This can be done by very simple means such as combing our hair or rubbing a glass rod with a silk cloth. However, to perform a useful function, we must free very large numbers of electrons and concentrate them in one area. This requires more sophisticated techniques. One device for doing this is the ordinary battery. There are many different types of batteries. Figure 1-13 shows two familiar examples. These are the dry cell (flashlight battery) and the wet cell (automobile battery).

While these two types of batteries are quite different in construction, they do have several points in common. Both have two terminals or poles to which an electrical circuit can be connected. Also, both employ a chemical reaction which produces an excess of electrons at one terminal and a deficiency of electrons at the other. The terminal at which the electrons congregate is called the negative terminal. It is indicated by the minus sign in Figure 1-13. The other terminal is indicated by a plus sign and has a deficiency of electrons. Now let's see how the battery affects the free electrons in a conductor.

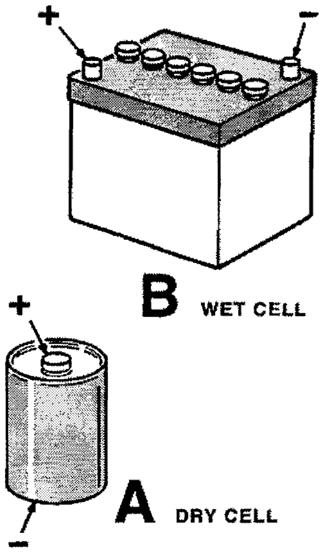


Figure 1-13
Two types of batteries.

Random Drift and Directed Drift

A conductor is a substance which has a large number of free electrons. In a conductor, the free electrons do not stand still. Instead they drift about in a random motion. Figure 1-14A represents a small section of a conductor containing many free electrons. At any instant, the free electrons are drifting at random in all directions. This is referred to as *random drift*. This type of drift occurs in all conductors, but it has little practical use. To do useful work, the free electrons must be forced to drift in the same direction rather than at random.

We can influence drifting electrons so that all, or most, electrons move in the same direction through the conductor. This can be done by placing electrical charges at opposite ends of the conductor. Figure 1-14B shows a negative charge placed at one end of the conductor while a positive charge is placed at the other. The negative charge repels the free electrons, while the positive charge attracts them. As a result, all of the free electrons move or drift in the same general direction. The direction is from the negative charge to the positive charge.

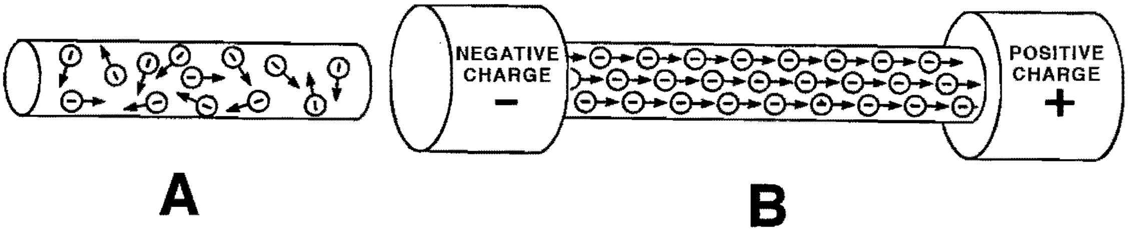


Figure 1-14
Completion of random and directed drift.

Here, the application of the electrical charges at the ends of the conductor has changed random drift to directed drift. This directed drift of free electrons is called *flow*. We say that an *electric current* is flowing through the conductor. If the electrical charges shown in Figure 1-14B are isolated from one another, the flow of electrons will quickly cancel both charges and only a momentary current will flow. However, if the two electrical charges are caused by a battery, the chemical action of the battery can maintain the two charges for some time. Therefore, a battery can maintain a continuous current through a conductor for a long period.

A copper wire is a good example of a conductor. Figure 1-15 shows a length of copper wire connected from one terminal to the other of a battery. A heavy current will flow from the negative terminal of the battery to the positive terminal. Recall that the negative terminal is a source of free electrons. An electron at this point is repelled by the negative charge and is attracted by the positive charge at the opposite terminal. Thus, the electrons flow through the wire as shown. When they enter the positive terminal of the battery, they are captured by positive ions. The chemical reaction of the battery is constantly releasing new free electrons and positive ions to make up for the ones lost by recombination.

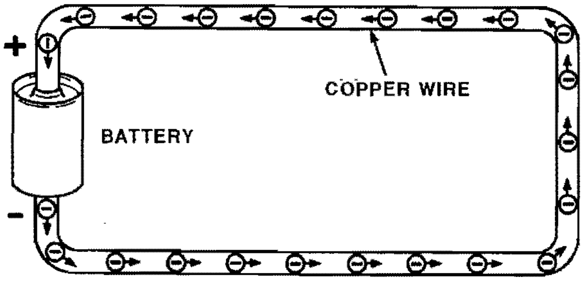


Figure 1-15
Current flows from the negative terminal to the positive terminal of the battery.

It should be pointed out that in practice, we never connect a conductor directly across the terminals of the battery as shown in Figure 1-15. The heavy current would quickly exhaust the battery. This is an example of a "short circuit" and is normally avoided at all cost. This example is shown here merely to illustrate the concept of current flow.

Programmed Review

31. Current is the flow of electrical charges from one point to another. Since electrons carry electrical charges, current can also be defined as the flow of ____________ .

32. (electrons) Before electrons can participate in current flow, they must first be freed from the atom. When an electron is dislodged from an atom, the atom becomes a positive ____________ .

33. (ion) Electrons are distributed around the atom in shells. Of particular importance to electronics is the outer shell. This shell is called the valence shell. Also, the electrons in this shell are called ____________ electrons.

34. (valence) These are the electrons which can be most easily freed from the atom. However, the valence electrons in some elements are very difficult to dislodge while in other elements they are freed easily. The difference stems from the number of electrons in the ____________ shell.

35. (valence) If the valence shell contains one or two electrons, they can be easily dislodged. However, when the shell is full, or nearly full, the electrons are very difficult to dislodge. Therefore, the ease with which an electron can be dislodged depends largely upon the ____________ of electrons in the valence shell.

36. (number) A conductor is defined as a substance which has a large number of free electrons. Thus, elements which have only one or two electrons in their valence shell normally are good ____________ .

37. (conductors) Elements such as gold, silver, and copper have only one valence electron. Therefore, these elements are very good __________.

38. (conductors) On the other hand, an insulator is defined as a substance which has very few free electrons. This situation occurs in elements which have their valence shells nearly full. For example, elements with 6 or 7 valence electrons make good ____________ .

39. (insulators) The free electrons within a conductor drift around at random. To do useful work, these electrons must be forced to drift in a desired direction. We can influence electron drift by connecting the conductor across a battery. A battery is a device which has an excess of electrons at one terminal and a deficiency of electrons at the other. The terminal with an excess of electrons is called the negative terminal. The terminal with the deficiency of electrons is called the ____________ terminal.

40. (positive) If one end of a conductor is connected to the negative terminal and the other end is connected to the positive terminal, electrons will flow through the conductor. In the conductor, electrons will always flow from the negative terminal to the ____________ terminal.

41. (positive) Electrons which leave the negative terminal of the battery are replaced by other electrons which are released by the chemical reaction within the battery. Thus, a battery can maintain a continuous flow of electrons through a conductor for a long period of time. This flow of electrons is called *current*. Electrons flow from a ____________ charge to a ____________ charge.

42. (negative, positive).

THE ELECTRIC CIRCUIT

In its simplest form, an electric circuit consists of a power source, a load, and conductors for connecting the power source to the load. The power source is often a battery. The purpose of the power source is to provide the force necessary to direct electron flow. As you will see in the next unit, this force is called *voltage*. Power sources produce voltage by creating a positive charge at one terminal and a negative charge at the other.

A *load* is generally some kind of electrical device which performs a useful function. It might be a lamp which produces light, a motor which produces physical motion, a horn which produces sound, or a heating element which produces heat. Regardless of the type of load used, the load performs its useful function only when electric current flows through it.

The third part of the circuit is the conductors which connect the power source to the load. They provide a path for current flow. The conductor may be a length of copper wire, a strip of aluminum, the metal frame of an automobile, etc.

Figure 1-16 shows a pictorial representation of an electric circuit consisting of a battery, a lamp, and connecting copper wires. The battery produces the force (voltage) necessary to cause the directed flow of electrons. The force developed by the battery causes the free electrons in the conductor to flow through the lamp in the direction shown. The free electrons are repelled by the negative charge and are attracted by the positive charge. Thus, the electrons flow from negative to positive. The negative and positive charges in the battery are constantly being replenished by the chemical action of the battery. Therefore, the battery can maintain a current flow for a long period of time. As the electrons flow through the lamp, they heat up the wire within the lamp. As the wire becomes hotter, the lamp emits light. The lamp will glow as long as a fairly strong current is maintained.

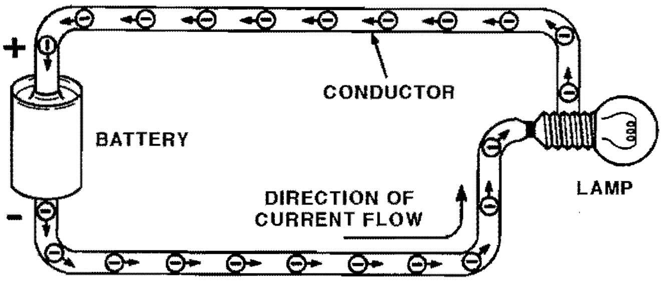


Figure 1-16
A simple electric circuit.

We know from our experiences with flashlights, that a battery cannot maintain a constant current flow forever. As the battery is used, the chemical reaction within the battery slows down and eventually the battery produces no current at all. At this time, it is said to be dead, or run down. For this reason, it is necessary to add a component to our simple electrical circuit.

The circuit in Figure 1-16 can be made much more practical by adding a control. In this case, the control is a switch which provides a simple method of turning the lamp on and off. Since some type of control is necessary, you could say that a basic practical circuit consists of four parts; the power source, the load, the conductor, and the control.

Figure 1-17 shows the circuit after the switch has been added. For simplicity, a "knife" switch is shown. It consists of two metal contacts to which conductors may be connected, a metal arm which can be opened and closed, and a base. Current cannot flow through the base of the switch because it is made of insulator material. Current can flow only through the arm and then only if the arm is closed.

In Figure 1-17A, the switch is shown closed. With the switch closed, there is a path for current flow from the negative terminal of the battery through the switch and lamp to the positive terminal. The lamp lights because current flows through it. When the switch is opened as shown in Figure 1-17B, the path for current flow is broken. Thus, the lamp does not glow because there is no current flowing through it.

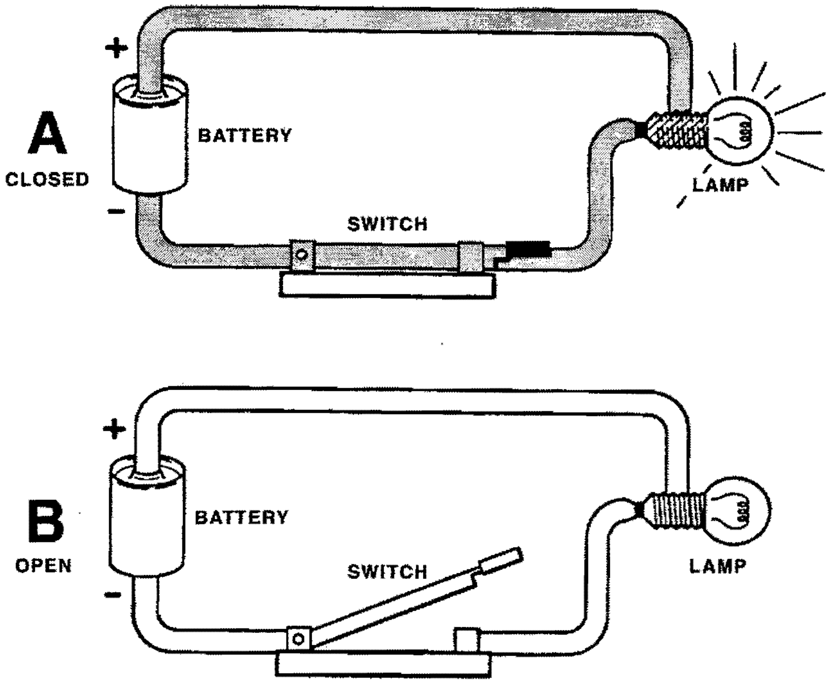


Figure 1-17
A circuit with a switch.

While simple circuits can be drawn as shown in Figures 1-16 and 1-17, it would be very difficult to draw complex circuits in this manner. For this reason, the *schematic diagram* was developed. A schematic diagram is a drawing in which symbols are used to represent circuit components. Thus, the first step to understanding a schematic diagram is to learn the symbols for the various components used. Figure 1-18 compares the schematic symbol with the pictorial representation of the circuit components we have used up to this point. The conductor is represented by a single line in the schematic. Also, the picture of the battery is replaced by a series of long and short lines. The long line represents the positive terminal while the short line represents the negative terminal. The same symbol can be used regardless of the type of battery. The symbols for the lamp, switch and resistor are also shown. Resistors will be discussed in detail in Unit 3.

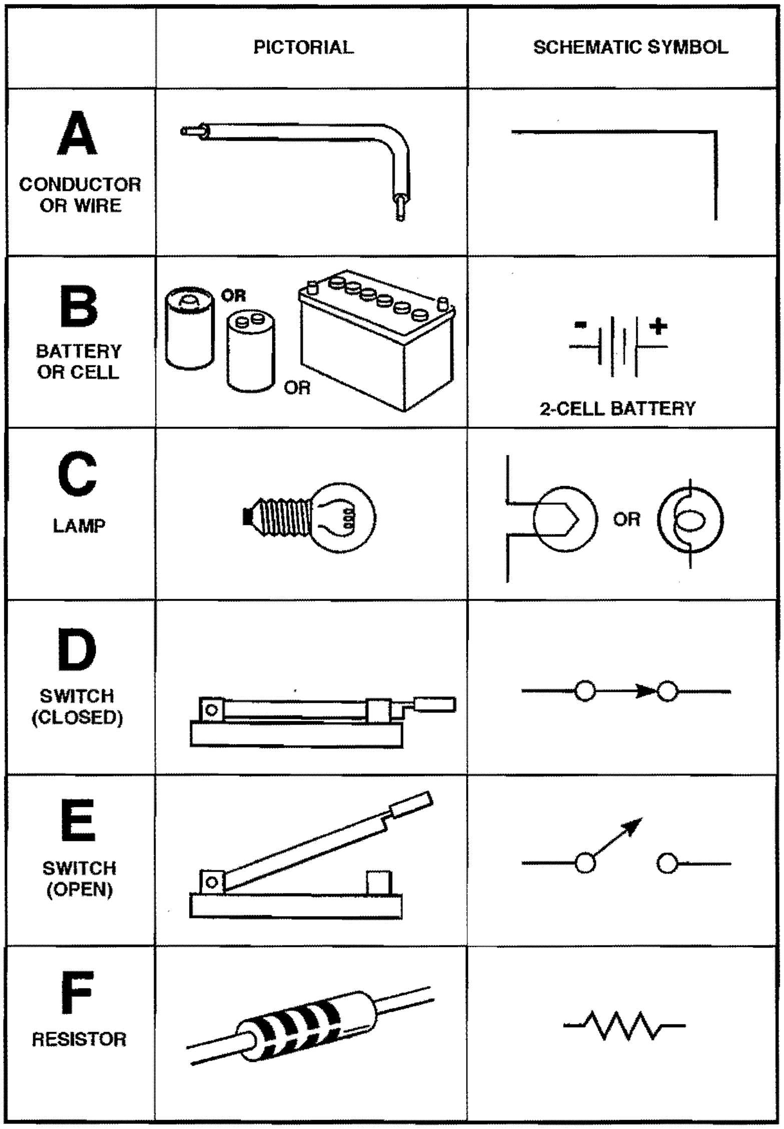

PICTORIAL
SCHEMATIC SYMBOL
A
CONDUCTOR OR WIRE
B
BATTERY OR CELL
OR
OR
-
+
2-CELL BATTERY
C
LAMP
OR
D
SWITCH (CLOSED)
E
SWITCH (OPEN)
F
RESISTOR

Figure 1-18
Pictorial representations compared with the schematic symbols.

Figure 1-19 shows several of the symbols combined to form a schematic diagram. Figure 1-19A is the schematic diagram for the pictorial drawing shown earlier in Figure 1-17A. Also, Figure 1-19B is a schematic diagram of the pictorial shown in Figure 1-17B.

The circuit shown in Figure 1-19 is the schematic diagram of a flashlight. It is also the diagram for the headlight system in an automobile. In fact it can represent any system which contains a battery, a lamp, and a switch. If the lamp is replaced with a motor, the circuit becomes that of the starter system in a car. In this case, the switch is operated by the ignition key. Other circuits which operate in a similar manner are the doorbell and the automobile horn. In the first case, the bell is the load while the switch is operated by a push button at the door. In the second case, the horn is the load while the switch is located on the steering wheel.

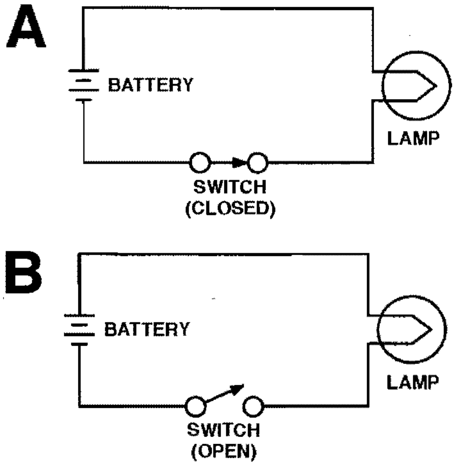


Figure 1-19
Schematic diagram of a simple circuit.

Programmed Review

43. An electric circuit consists of a power source connected to a load. The power source provides the force which causes electrons to flow. This force is called voltage. In a flashlight the power source is a ____________.

44. (battery) The load is a device which performs some useful function. The load's function may be to produce light, sound, or motion. Thus, lamps, horns, and motors are examples of ____________ .

45. (loads) The load performs its function when current flows through it. Most loads do not perform continuously. Instead the current is turned on and off by some kind of ____________ .

46. (control) Schematic diagrams are used as a shorthand method of drawing electric circuits. The schematic diagram differs from a pictorial presentation in that the components are drawn as ____________ .

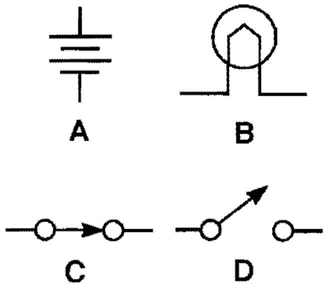


Figure 1-20
Identify these symbols.

47. (symbols) Shown in Figure 1-20 are the schematic symbols for four different components. Identify each one.

a. ____________
b. ____________
c. ____________
d. ____________

48. (a. battery, b. lamp, c. closed switch, d. open switch) The symbol for the battery has a short line at one end and a long line at the other. The short line represents the ____________ terminal.

49. (negative) Figure 1-19 on the previous page shows a complete electrical circuit. When the switch is closed, electrons flow from the ____________ terminal of the battery through the lamp to the ____________ terminal.

50. (negative, positive)

MEASURING CURRENT

Current is the flow of electrons from a negative to a positive charge. To measure current flow, we must measure the number of electrons flowing past a point in a specific length of time. Before we discuss how current is measured, we must first define the unit of electrical charge and the unit of current.

The Coulomb

We have seen that the charge on an object is determined by the number of electrons which the object loses or gains. If the object loses electrons, the charge is positive. However, an object which gains electrons has a negative charge. The unit of electrical charge is called the *coulomb*. The coulomb is equal to the charge of 6.25×10^{18} electrons. For those who are not used to expressing numbers in this way, the number is:

6,250,000,000,000,000,000.

An object which has gained 6.25×10^{18} electrons has a negative charge of one coulomb. On the other hand, an object which has given up 6.25×10^{18} electrons has a positive charge of one coulomb.

Powers of Ten and Scientific Notation

A word about powers of ten and scientific notation may be helpful at this point. The number 6,250,000,000,000,000,000 can be expressed as 6.25×10^{18}. This number is read "six point two five times ten to the eighteenth power." The expression "ten to the eighteenth power" means that the decimal place in 6.25 should be moved 18 places to the right in order to convert it to the proper number. The theory is that it is easier to write and remember 6.25×10^{18} than it is to write and remember 6,250,000,000,000,000,000. This shorthand method of expressing numbers is known as powers of ten or scientific notation. It is often used in electronics to express very large and very small numbers. Very small numbers are expressed by using negative powers of ten. For example, 3.2×10^{-8} is scientific notation for the number 0.000000032. Here, "ten to the minus eighth power" means "move the decimal place in 3.2 eight places to the left." To be sure you have the idea, let's look at some examples of both positive and negative powers of ten:

Positive Powers of Ten

$7.9 \times 10^{4} = 79{,}000$
$9.1 \times 10^{8} = 910{,}000{,}000$
$1.0 \times 10^{12} = 1{,}000{,}000{,}000{,}000$

Negative powers of Ten

$7.9 \times 10^{-4} = 0.00079$
$9.1 \times 10^{-8} = 0.000\ 000\ 091$
$1.0 \times 10^{-12} = 0{,}000\ 000\ 000\ 001$

Study these examples until you get the idea of writing numbers with this system. If you feel you need additional explanation, read Appendix A at the end of this text. It is a programmed instruction sequence designed to teach powers of ten and scientific notation in much greater detail.

The Ampere

The unit of current is the ampere. The ampere is the rate at which electrons move past a given point. As mentioned above, 1 coulomb is equal to 6.25×10^{18} electrons. An ampere is equal to *1 coulomb per second.* That is, if 1 coulomb (6.25×10^{18} electrons) flows past a given point in 1 second, then the current is equal to 1 ampere. Coulombs indicate numbers of electrons; amperes indicate the rate of electron flow or coulombs per second.

When 6.25×10^{18} electrons flow through a wire each second, the current flow is 1 ampere. If twice this number of electrons flows each second, the current is 2 amperes. This relationship is expressed by the equation:

$$\text{amperes} = \frac{\text{Coulombs}}{\text{seconds}}$$

If 10 coulombs flow past a point in two seconds, then the current flow is 5 amperes.

The name ampere is often shortened to *amp* and is abbreviated A. Many times the ampere is too large a unit. In these cases metric prefixes are used to denote smaller units. The milliampere (mA) is one thousandth (.001) of an ampere. The microampere (μA) is one millionth (.000 001) of an ampere. In other words, there are 1000 milliamperes or 1,000,000 microamperes in an ampere.

We change from amperes to milliamperes by multiplying by 10^3. Thus, 1.7 amperes is equal to 1.7×10^3 milliamperes. Also, we change from amperes to microamperes by multiplying by 10^6. Therefore, 1.7 amperes is equal to 1.7×10^6 microamperes.

For those who need it, a more detailed explanation of metric prefixes is provided in Appendix A.

The Ammeter

An *ammeter* is a device for measuring current flow. The name *ammeter* is a shortened form of the name ampere meter. Figure 1-21 shows a diagram of an ammeter. It has a pointer which moves in front of a calibrated scale. In this figure, the scale is calibrated from 0 to 10 amperes. The movement of the pointer is proportional to the amount of current flowing through the meter. Therefore, an accurate indication of the amount of current flowing in a circuit is obtained by reading the pointer against the scale. This meter is presently displaying a reading of just over 6 amperes.

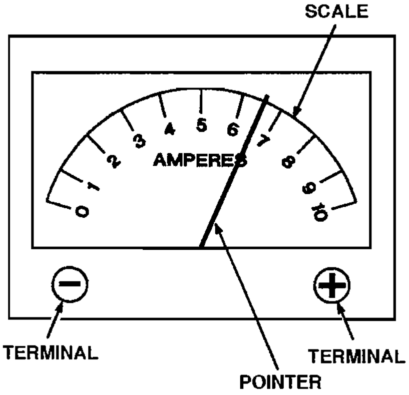


Figure 1-21
Ammeter.

Figure 1-22A shows a circuit in which an unknown amount of current is flowing. We can measure this current by inserting an ammeter into the circuit as shown in Figure 1-22B. Notice that the schematic symbol for the ammeter is a circle with the letter A. Before the ammeter can measure current, it must be placed in the circuit in such a way that the current we wish to measure actually flows through the meter. We say that the ammeter is connected in series with the circuit elements. Incidentally, a circuit like the one shown in Figure 1-22B is called a *series* circuit. In a *series* circuit, the same current flows through all of the elements in one continuous loop.

The maximum current that an ammeter can safely measure is indicated by the highest number on the scale. The highest current that the ammeter in Figure 1-21 can safely measure is 10 amperes. This is called its full scale reading. Many current meters are much more sensitive. Some have a full scale reading of 1 milliampere. Others provide a full scale reading with only 50 microamperes flowing through them.

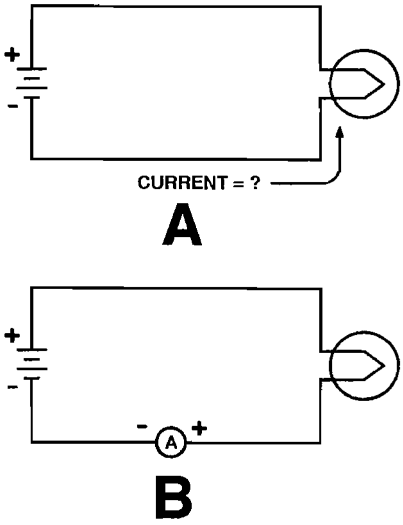


Figure 1-22
Measuring current.

Ammeters are delicate instruments that can be destroyed if the applied current greatly exceeds the full scale reading of the meter. For this reason, we must exercise certain precautions when using the ammeter.

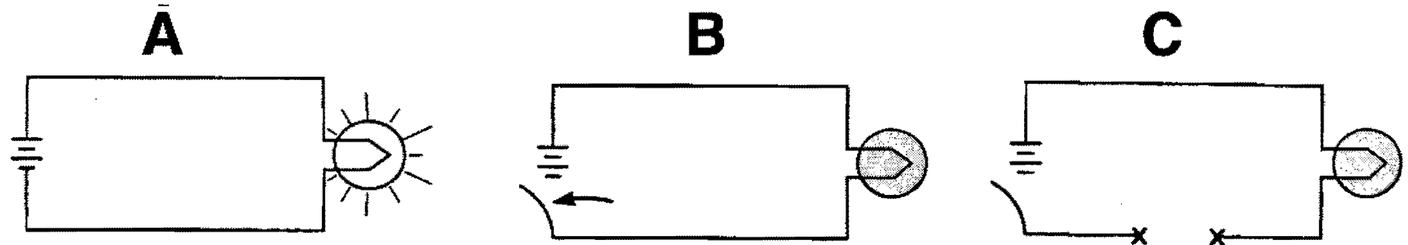
To protect yourself and the ammeter, there is a definite procedure which you must follow when you use an ammeter. The first step is to insure that the ammeter you are using is heavy enough for the job. As mentioned above, if the current rating is exceeded, the meter may be damaged.

The second step is to remove power from the circuit to be tested. In battery powered circuits this can be done by removing the battery or by disconnecting one of the battery leads. The purpose of this step is to protect yourself from electrical shock as you connect the ammeter.

The third step is to break the circuit at the point where the current is to be measured. The circuit must be broken because the ammeter must be placed in series with the circuit.

Fourth, you must observe polarity while you connect the ammeter into the circuity. The ammeter has two terminals labeled negative and positive. Current must flow through the ammeter from the negative terminal to the positive terminal. Thus, the wire from the negative terminal of the battery must lead to the negative terminal of the ammeter. If the ammeter is connected backwards, the pointer will attempt to deflect backwards and may end up bent or broken. Observing polarity simply means that the negative terminal of the ammeter is connected to the wire that leads to the negative terminal of the battery. Naturally, the positive terminal of the ammeter is connected to the wire that leads to the positive side of the battery.

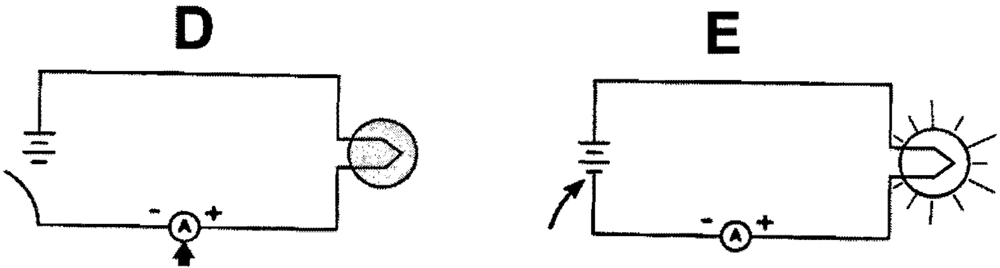
Finally, power is reapplied to the circuit and the current is read from the ammeter scale. Figure 1-23 illustrates this step-by-step procedure.



CIRCUIT IN WHICH CURRENT IS TO BE MEASURED.

REMOVE POWER BY DISCONNECTING ONE SIDE OF BATTERY.

BREAK CIRCUIT AT POINT WHERE CURRENT IS TO BE MEASURED.



CONNECT METER, OBSERVE POLARITY.

RESTORE POWER AND READ CURRENT.

Figure 1-23

Procedure for measuring current.

Programmed Review

51. The unit of electrical charge is the coulomb. The coulomb is equal to the charge of 6.25 x 10^{18} electrons. Thus, if an object has an excess of 6.25 x 10^{18} electrons, it has a negative charge of one ___________ .

52. (coulomb) On the other hand, an object which has given up 6.25 x 10^{18} electrons has a ___________ change of one coulomb.

53. (positive) The unit of current is the ampere. The ampere is a measure of the rate at which electrons pass a point in a specific length of time. The ampere can be thought of as 1 coulomb per second. If one coulomb per second flows through a wire, the current in the wire is one ___________.

54. (ampere) The abbreviation for ampere is A. Smaller units of current are the milliampere (mA) and the microampere (µA). The milliampere is equal to 10^{-3} or 0.001 amperes while the microampere is equal to 10^{-6} or 0.000 001 amperes. Stated another way the milliampere is one-thousandth of an ampere while the microampere is one - ___________ of an ampere.

55. (millionth) A device for measuring current is the ammeter. The ammeter must be placed in the circuit so that the current to be measured flows through it. That is, the ___________ must be connected in series with the circuit.

56. (ammeter) In addition, we must observe polarity when connecting the ammeter in a circuit. This means that the negative lead of the ammeter is connected to the wire which leads to the negative side of the battery. Also, the positive lead must be connected to the wire that leads to the ___________ side of the battery.

57. (positive)

EXPERIMENT 1

Measuring Current

OBJECTIVES: *To practice measuring current.*

To familiarize yourself with the operation of your Heathkit Analog Trainer.

To familiarize yourself with your ammeter (multimeter).

Introduction

The current used in this experiment is provided by your Heathkit Analog Trainer. The power supply section of two typical trainers is shown in Figure 1-24. These provide the variable DC voltages necessary to perform the experiments for this course.

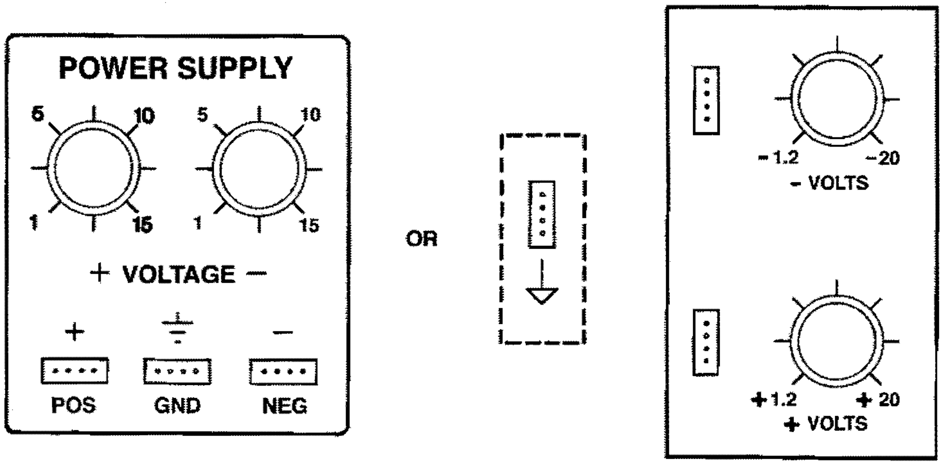

POWER SUPPLY
5
10
5
10
1
15
1
15
+ VOLTAGE −
+
−
POS
GND
NEG
OR
−1.2
−20
− VOLTS
+1.2
+20
+ VOLTS

Figure 1-24
Typical power supply sections on the Trainer.

The supply voltages are controlled by the + and – voltage control knobs respectively. These voltages are referenced to the GND (ground) terminal, which is at zero volts.

Notice that the + voltage supply is capable of providing positive voltages of at least 15 volts above ground and the – voltage supply is capable of providing at least 15 volts below ground. When both of these controls are adjusted to maximum, that is fully clockwise (cw), there will be over 30 volts DC present between the positive and negative connector terminals.

Before you continue, read over the instructions provided with your meter. Be sure you understand the various ranges and scales. You will be using your meter as an ammeter (set to measure DC). Also, review the operations section of your Trainer Manual.

Material Required

1 — Heathkit Analog Trainer
1 — Ammeter (multimeter) capable of measuring up to 500 milliamperes with test leads
1 — Roll of #22 (insulated) copper wire
1 — One foot length of #22 nichrome wire (no insulation)
1 — 15-ohm, 5%, 1/2-watt resistor (brown-green-black-gold)
1 — Diagonal wire cutter/wire stripper

Procedure

1. Be sure the Trainer power is OFF. Then plug in its line cord.

NOTE: Throughout the experiments you should understand that all circuits are built and checked with the Trainer power OFF unless a step directs you otherwise.

2. Set your multimeter to measure current in the 500 milliampere (mA) range.

3. Attach the negative lead of your meter to the GND terminal on your Trainer. You may need to insert a short jumper wire into the GND terminal to make the connections to the meter lead. If your meter does not have a clip lead, a jumper wire with alligator clips on each end is a handy way to make meter/circuit connections.

NOTE: The experiments you will be performing generally require one or more breadboard "jumper" wires. To prepare these, measure off the length required, cut it, and then remove (strip) about 1/4-inch of insulation from each end to allow breadboard insertion.

4. Refer to Figure 1-25A for the connection scheme of the "solderless" breadboard. Notice that each vertical insertion point is internally connected to the others in its column. This allows several components to be electrically connected by inserting their leads into different holes in the same column. There is no internal connection between different columns or rows.

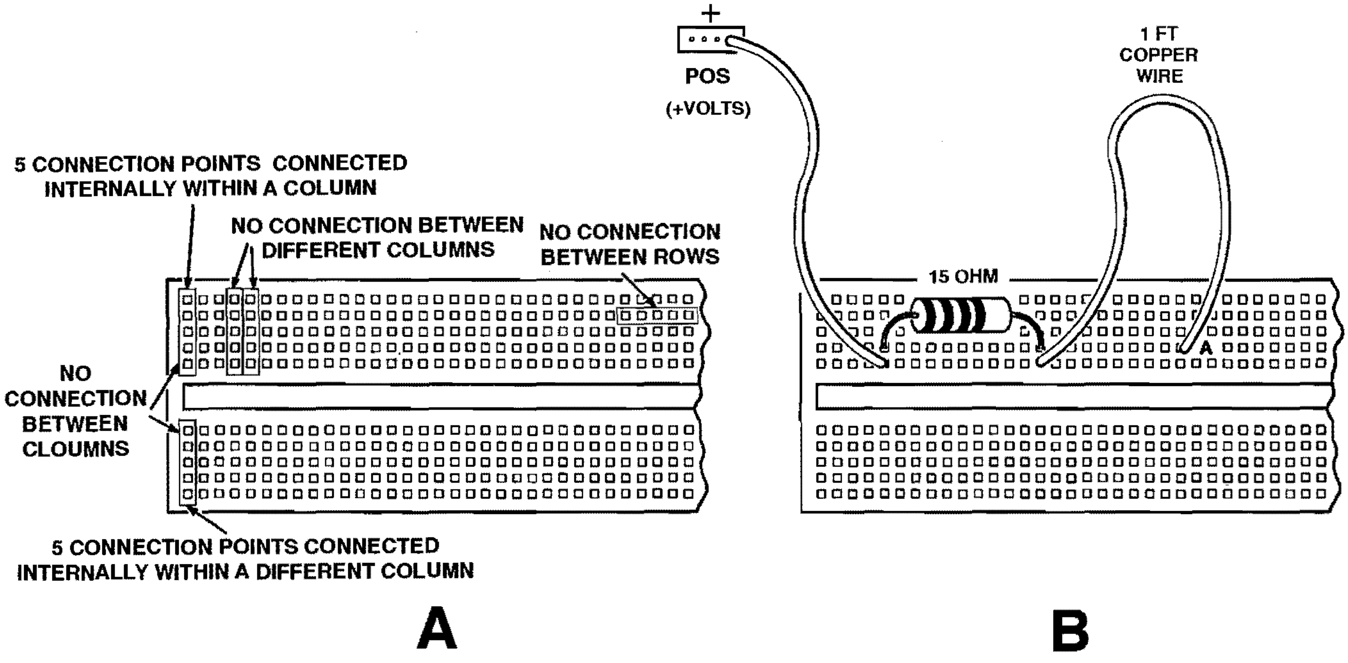

+
POS
(+VOLTS)
1 FT
COPPER
WIRE
5 CONNECTION POINTS CONNECTED INTERNALLY WITHIN A COLUMN
NO CONNECTION BETWEEN DIFFERENT COLUMNS
NO CONNECTION BETWEEN ROWS
15 OHM
A
NO CONNECTION BETWEEN CLOUMNS
5 CONNECTION POINTS CONNECTED INTERNALLY WITHIN A DIFFERENT COLUMN
A
B

Figure 1-25

Trainer breadboard connections.

5. With the POS voltage control set fully counterclockwise (ccw), construct the circuit shown in Figure 1-25B. Use a one foot length of #22 copper (insulated) wire for the large loop in the circuit and the 15 ohm resistor as the load. Leave the negative lead of your ammeter connected to the GND terminal. Connect the positive lead of your ammeter to the end of the copper wire at point A in Figure 1-25B.

6. Now switch the Trainer on and observe the current as measured by your ammeter. Check to see if you can now use a different range on your meter. To do this, switch your meter's current level selector to a lower value, for example, 250 mA. As long as the current you are attempting to measure does not exceed the range setting of your meter,* a lower range will make a more accurate reading possible. The current measured is _________ mA.

---

* Caution: If the current you are attempting to measure does exceed the range setting of your meter, the meter pointer will go "off scale" and, depending upon the type of meter, may even become damaged. This is why it is good practice to select a high meter setting at first, then decrease the setting for accuracy later.

7. Switch the Trainer off. Replace the 1 foot length of copper wire in your circuit with 1 foot of (uninsulated) nichrome wire. Leave the meter connected as it was in step 5 to measure current.

8. Switch the Trainer on. Again observe the current indicated by your ammeter. The current measured now is __________ mA. Is this current greater than, less than, or equal to the current measured in step 6? __________ Switch the Trainer OFF.

Discussion

In this experiment you gained some experience in using both the Trainer and your meter. In step 6 of the experiment you measured the current that flowed in a circuit consisting of a 15-ohm resistor in series with one foot of #22 copper wire. The current through this circuit should have been about 80 milliamperes. Your figures may vary somewhat from this value as a result of component, Trainer, and instrument tolerances.

In step 8 you again measured the current through the circuit. This time, however, you were measuring the current through the circuit using the nichrome wire. The current through this circuit should have been slightly less than it was in step 6 (about 75 milliamperes).

Note that these two circuits appear essentially the same, yet there is a difference of about 5 milliamperes in current flow. The only change you made to the original circuit was to substitute the nichrome wire for the copper wire. We can conclude from this that, if all other conditions remained the same, current traveled at a different rate through different wires, due to the difference in what they are made of—in this case copper versus nichrome. The copper wire allows electrons to pass at higher rate (more electrons per second) than the nichrome wire does. Later on you will see that this phenomena is characterized by a property called the "resistance" of a material. That is, given the same voltage, current will flow at a higher rate through a material that has less resistance than through one with a greater resistance.

SUMMARY

Following is a summary of the important points that were discussed in Unit 1. If you have a question on any point presented here, reread that portion of the text which covered this point.

Matter is anything which has weight and occupies space.

All matter is comprised of one or more of the elements.

A compound is a substance comprised of two or more elements.

The smallest particle of a compound is a molecule.

A molecule consists of two or more atoms bound together.

The atom is the smallest particle into which an element can be divided.

There are 92 different types of atoms that occur in nature.

Another dozen or more have been artificially made by man.

Atoms are comprised of electrons, protons, and neutrons.

The nucleus contains protons and neutrons.

Electrons orbit the nucleus.

The type of atom is determined by the number of electrons, protons, and neutrons.

Electricity is a property that electrons and protons have which causes them to behave in certain predictable ways.

The electron has a negative electrical charge.

The proton has a positive electrical charge.

An electrostatic field surrounds every charged particle.

Coulomb's Law describes the action of charged particles. It states that like charges repel, while unlike charges attract.

An atom has a neutral charge when it contains the same number of electrons and protons.

An atom which has a net electrical charge called an ion.

Electrical charges can be produced in certain materials by friction.

An electrical charge can be partially transferred from a charged object to an uncharged object by touching the two objects together.

An electrical charge can be induced into a neutral object by bringing a charged object near it.

In its simplest form, a circuit consists of a power source, a load, and conductors that connect the power source to the load.

In electronics, current is defined as the flow of electrical charge from one point to another.

Before an electron can participate in current flow, it must be freed from its atom.

The centrifugal force of the orbiting electron is exactly offset by the attraction of the positive charge in the nucleus.

Electrons are distributed in shells.

The outer shell is called the valence shell.

Valence electrons are the ones important in electronics because they are the ones which can be freed to contribute to current flow.

The number of valence electrons determines if an element is a conductor or an insulator.

A conductor is a substance which has a large number of free electrons.

An insulator is a substance which has very few free electrons.

Most metals are good conductors.

A battery is a two-terminal device which produces an excess of electrons at one terminal and a deficiency of electrons at the other.

Free electrons normally drift around in a random pattern. However, they can be forced to flow in a desired direction.

Current flow is the directed drift of free electrons.

Electrons flow from negative to positive charges.

A schematic diagram uses symbols to represent electronic components.

The unit of electrical charge is the coulomb.

The coulomb is equal to 6.25×10^{18} electrons.

Current is the rate at which electrons flow past a point. The ampere is the unit of current.

The ampere is equal to one coulomb per second.

A milliampere is one thousandth of an ampere.

A microampere is one millionth of an ampere.

A device for measuring current is the ammeter.

The ammeter must be connected in series with the circuit under test.

You must observe polarity when you connect an ammeter into a circuit.

This concludes the summary of Unit 1. When you are certain that you understand all of these points, complete the Unit Examination.

UNIT EXAMINATION

1. A positive ion is produced when an atom:

   A. loses an electron.
   B. gains an electron.
   C. loses a proton.
   D. gains a proton.

2. Which of the following statements is true?

   A. The electron has a positive charge, the proton has a negative charge, and the neutron has no charge.
   B. The electron has a negative charge, the proton has a positive charge, and the neutron has no charge.
   C. The electron has a negative charge, the proton has no charge, and the neutron has a positive charge.
   D. The electron has a positive charge, the proton has no charge, and the neutron has a negative charge.

3. Which of the following statements is true?

   A. An electron attracts another electron.
   B. An electron attracts a negative ion.
   C. A proton repels an electron.
   D. An electron repels another electron.

4. There are two objects which have a deficiency of electrons. The two objects are:

   A. negatively charged and will repel each other.
   B. positively charged and will repel each other.
   C. negatively charged and will attract each other.
   D. positively charged and will attract each other.

5. An atom has a neutral charge when it has the same number of:

   A. electrons as neutrons.
   B. electrons as protons.
   C. protons as neutrons.
   D. electrons as ions.

6. Current is defined as the flow of:

   A. protons from a negative charge to a positive charge.
   B. protons from a positive charge to a negative charge.
   C. electrons from a negative charge to a positive charge.
   D. Electrons from a positive charge to a negative charge.

7. A substance which has few free electrons is called:

   A. an insulator.
   B. a conductor.
   C. an element.
   D. a compound.

8. The unit of electrical charge is the:

   A. volt.
   B. ampere.
   C. valence.
   D. coulomb.

9. The unit of current is the:

   A. volt.
   B. ampere.
   C. valence.
   D. coulomb.

10. The ampere is equal to:

    A. one volt per second.
    B. one coulomb.
    C. one thousand microamperes.
    D. one coulomb per second.

11. One milliampere is equal to:

    A. 0.001 amperes.
    B. 1000 amperes.
    C. 0.000 001 amperes.
    D. 1 000 000 amperes.

12. One ampere is equal to:

    A. 1000 microamperes.
    B. 0.001 microamperes.
    C. 0.000 001 microamperes.
    D. 1,000,000 microamperes.

13. Which of the following shows an ammeter connected properly for measuring the current through the lamp?

    A. Figure 1-26A.
    B. Figure 1-26B.
    C. Figure 1-26C.
    D. Figure 1-26D.

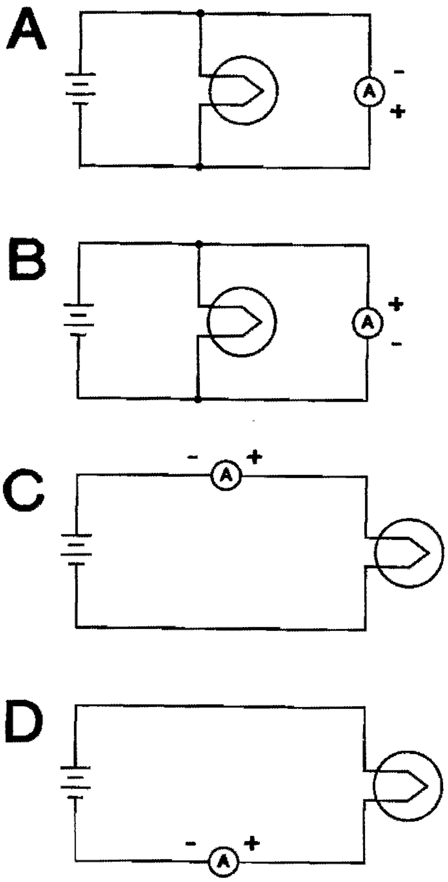


Figure 1-26

14. Which of the following is the correct schematic diagram of a closed switch, a battery, and a lamp connected in series?

    A. Figure 1-27A.
    B. Figure 1-27B.
    C. Figure 1-27C.
    D. Figure 1-27D.

15. In Figure 1-27B, the current through the circuit flows:

    A. in a clockwise direction.
    B. in a counterclockwise direction.
    C. in either direction.
    D. All of the above.

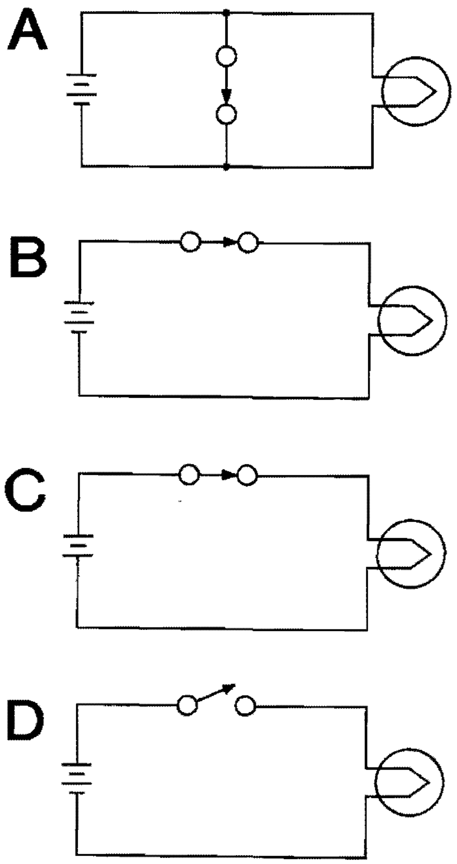


Figure 1-27

16. The four parts of a basic practical circuit are the:

    A. power source, control, switch, and conductor.
    B. power source, control, load, and ground.
    C. power source, control, load, and conductor.
    D. power source, load, light, and resistor.

EXAMINATION ANSWERS

1. A — The electron has a negative charge which is normally offset by the positive charge of a proton. When the atom loses an electron, it loses a negative charge and, therefore, has a net positive charge.

2. B — The electron has a negative charge. The proton has an equal but opposite (positive) charge. The neutron has no charge at all.

3. D — All electrons have negative charges. Since like charges repel, one electron repels another.

4. B — Objects with too few electrons have positive charges. Since they have like charges they repel each other.

5. B — To have a neutral charge, the negative charge of each electron must be cancelled by a positive charge of a proton.

6. C — Since electrons have a negative charge, they must flow from negative to positive charges.

7. A — Without free electrons, a substance cannot support current flow. A substance with few free electrons is an insulator.

8. D — The unit of electrical charge is the coulomb.

9. B — The unit of current is the ampere.

10. D — The ampere is equal to one coulomb per second.

11. A — A milliampere is one 1-thousandth of an ampere. One 1-thousandth is equal to 0.001.

12. D — A microampere is 1-millionth of an ampere. Thus, there are one million microamperes in an ampere.

13. D — This is the only diagram in which the ammeter is connected in series and polarity is observed.

14. B — In (A) the switch is not in series with the other two components.
    In (C) the symbol for the battery is incorrect.
    In (D) the switch is shown open.

15. B — The current through the circuit shown in Figure 1-27D flows in a counterclockwise direction.

16. C — The four parts of the basic practical circuit are the power source, the load, the conductor, and the control.

UNIT 2

VOLTAGE

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INTRODUCTION

In the previous unit, you learned that a battery produces a force which causes electrons to flow in a closed circuit. You did not learn very much about the force except that it is caused by electrical charges at the battery terminals. That is, the force is produced by an excess of electrons at one terminal and a deficiency of electrons at the other. This force is called an *electromotive force*. Literally, electromotive force means the force which *moves electrons*. The measure of this force is called voltage. In fact, the terms *electromotive force* and *voltage* are frequently used interchangeably although, strictly speaking, they do have slightly different meanings.

In this unit, you will learn more about voltage or electromotive force and several ways in which this force is produced and used. You will also learn how voltage is measured and several important laws concerning voltage. Finally, you will perform experiments which demonstrate some important concepts about voltage.

UNIT OBJECTIVES

When you complete this unit, you will be able to:

1. Define the following terms: Electromotive force (emf), potential difference, voltage, volt, cell, primary cell, secondary cell, voltage drop, voltage rise, ground, short, open, and battery.

2. List six different ways in which electromotive force can be produced.

3. Describe the proper method to connect a voltmeter to a circuit and measure voltage.

4. Determine the output voltage from batteries connected in series-aiding, series-opposing, parallel, or series-parallel configurations.

5. Given the magnitude and polarity of the two charges, state whether a potential difference exists between them.

6. Given the magnitude and polarity of two charges, state the direction of electron movement between them.

7. Name the factors that determine the voltage and current capacity of a cell.

8 Given a list of applications, match them with the effect produced by an emf.

9. Name the three main parts of a cell.

10. State the output voltage of a dry cell and a wet cell.

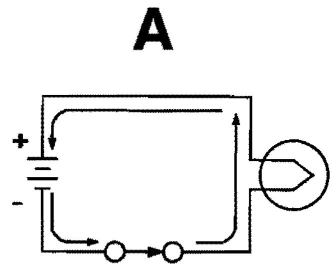
11. State the relationship between a voltage rise and a voltage drop.

UNIT ACTIVITY GUIDE

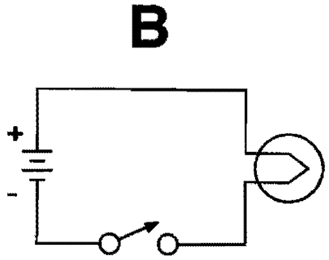
		Completion Time
☐	Read "Electrical Force."	________
☐	Complete Programmed Review frames 1-12.	________
☐	Read "Producing EMF."	________
☐	Complete Programmed Review frames 13-22.	________
☐	Read "Batteries."	________
☐	Complete Programmed Review frames 23-35.	________
☐	Read "Connecting Batteries."	________
☐	Complete Programmed Review frames 36-47.	________
☐	Read "Voltage Rises and Voltage Drops."	________
☐	Complete Programmed Review frames 48-56.	________
☐	Read "Concept of Ground."	________
☐	Complete Programmed Review frames 57-64.	________
☐	Read "Measuring Voltage."	________
☐	Complete Programmed Review frames 65-70.	________
☐	Perform Experiment 2.	________
☐	Perform Experiment 3.	________
☐	Perform Experiment 4.	________
☐	Study Summary.	________
☐	Complete Unit Examination.	________
☐	Check Examination Answers.	________

ELECTRICAL FORCE

You have seen that current will not flow in a circuit unless an external force is applied. In the circuits discussed in the previous unit, the force was provided by batteries. The battery changes chemical energy to electrical energy by separating negative charges (electrons) from positive charges (ions). These charges produce the force or pressure which causes electrons to flow and do useful work. This force is given several different names that are used more or less interchangeably. Let's examine the three most popular names and see what each name implies.



EMF CAUSES ELECTRONS TO FLOW IN CLOSED CIRCUIT



POTENTIAL FOR CURRENT FLOW EXISTS EVEN THOUGH THERE IS NO CURRENT

Figure 2-1
Emf and potential difference.

Electromotive Force (EMF)

One popular name is *electromotive force*, which is abbreviated *emf.* This name is very descriptive since it literally means a force which moves electrons. Thus, emf is the force or pressure which sets electrons in motion. This force is a natural result of Coulomb's law. You will recall that Coulomb's law states that like charges repel while unlike charges attract. The battery, by chemical action, produces a negative charge at one terminal and a positive charge at the other. The negative charge is simply an excess of electrons while the positive charge is an excess of positive ions. If a closed circuit is connected across the battery as shown in Figure 2-1A, a path for electron flow exists between the battery terminals. Free electrons are repelled by the charge on the negative terminal and are attracted by the charge on the positive terminal. The two opposite charges exert a pressure which forces the electrons to flow. Thus, the force or pressure is the result of the attraction of the unlike charges. To summarize, emf is the force which sets electrons in motion in a closed circuit.

Potential Difference

Another name for this force is potential difference. This name is also very descriptive. It describes the characteristics of emf in an open circuit. Emf is the force which causes electrons to move as shown in Figure 2-1A. However, consider the situation shown in Figure 2-1B. Here, electrons cannot flow because the switch is open. Nevertheless, the battery still produces the same pressure or force as before. Thus, the *potential* for producing current flow exists even though no current presently flows. As used here, *potential* means the possibility of doing work. If the switch is closed, current flows, the lamp lights, and useful work is done. Therefore, whether a battery is connected into a circuit or not, it has the potential for doing work.

Actually, any charge has the potential for doing work. For example, it can move another charge either by attraction or repulsion. Even a single electron can repel another electron. If one electron moves as the result of the action of the other electron, some small amount of work is done. In the battery, we are concerned with two different types of charges rather than a single charge. The electrons at the negative terminal are straining to rush to the positive terminal and cancel out the positive charge there. In the same way, the positive ions at the other terminal are straining to draw the electrons. We call this force *potential difference*. It is the potential for doing work that exists between two *different* charges.

The amount of work that can be done must be related in some way to the characteristics of the charges. We can illustrate this point by considering some static charges. Figure 2-2A shows a small negative charge separated from a small positive charge. Let's assume that charge A has an excess of one million electrons while charge B has a deficiency of one million electrons. If a conductor is connected between the two charges, electrons will flow from the negative to the positive charge. The work done here is moving of electrons. To cancel the two charges, one million electrons will flow from charge A to charge B.

Now consider what happens if the two charges are doubled as shown in Figure 2-2B. Here charge A has an excess of two million electrons while charge B has a deficiency of two million electrons. If a conductor is connected between the two charges, then two million electrons will rush from charge A to charge B. Thus, twice as much work is done.

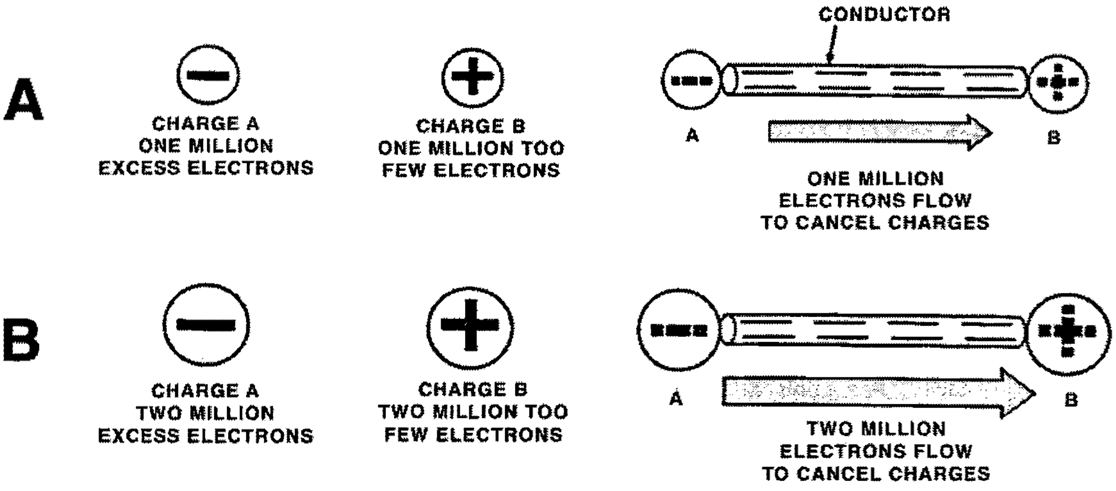

CONDUCTOR
A
CHARGE A
ONE MILLION
EXCESS ELECTRONS
CHARGE B
ONE MILLION TOO
FEW ELECTRONS
A
B
ONE MILLION
ELECTRONS FLOW
TO CANCEL CHARGES
B
CHARGE A
TWO MILLION
EXCESS ELECTRONS
CHARGE B
TWO MILLION TOO
FEW ELECTRONS
A
B
TWO MILLION
ELECTRONS FLOW
TO CANCEL CHARGES

Figure 2-2
Static charges have
the potential of doing work.

However, the magnitude of the charges is not the important consideration. It is the difference between the two charges that is important. Figure 2-3 illustrates that no work can be done if both charges have the same polarity and magnitude. In Figure 2-3A two charges are shown. Each has a negative charge caused by an excess of ten million electrons. How much work is done if these two charges are connected by a conductor? The answer, of course, is that no work is done. Because the two objects have exactly the same charge, no electrons can flow from one to the other. Thus, there is no potential for doing work. Figure 2-3B shows that the same is true for equal positive charges.

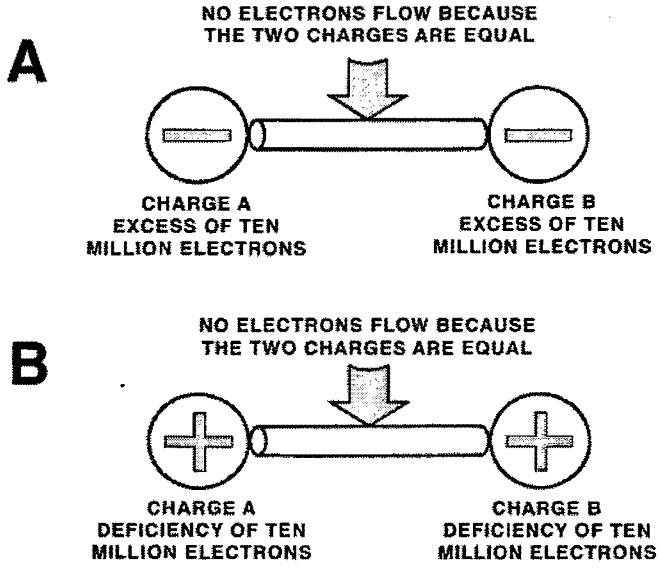

A
NO ELECTRONS FLOW BECAUSE THE TWO CHARGES ARE EQUAL
CHARGE A EXCESS OF TEN MILLION ELECTRONS
CHARGE B EXCESS OF TEN MILLION ELECTRONS
B
NO ELECTRONS FLOW BECAUSE THE TWO CHARGES ARE EQUAL
CHARGE A DEFICIENCY OF TEN MILLION ELECTRONS
CHARGE B DEFICIENCY OF TEN MILLION ELECTRONS

Figure 2-3
No potential for doing work exists between equal charges.

The potential to move electrons exists between any two unlike charges. That is, when two charges are different, electrons will flow from one charge to the other if given the chance. Charges can differ in two ways. First, they can be of opposite *polarity*. This simply means that one is positive and the other is negative as shown in Figure 2-2. Second, they can have different *magnitudes*. For example, Figure 2-4A shows two charges which have the same polarity (negative) but have different magnitudes. Charge A is more negative because it has more excess electrons than charge B. If a conductor is connected between the two charges as shown in Figure 2-4B, electrons flow from the greater negative charge to the less negative charge. The number of electrons will be exactly the right amount to equalize the two charges. In this example, charge A originally has three million excess electrons while charge B has only one million excess electrons. To equalize the two charges, one million electrons flow from charge A to charge B. Electron flow ceases as soon as the two charges become equal. Notice that the direction of current flow is from the more negative charge to the less negative charge.

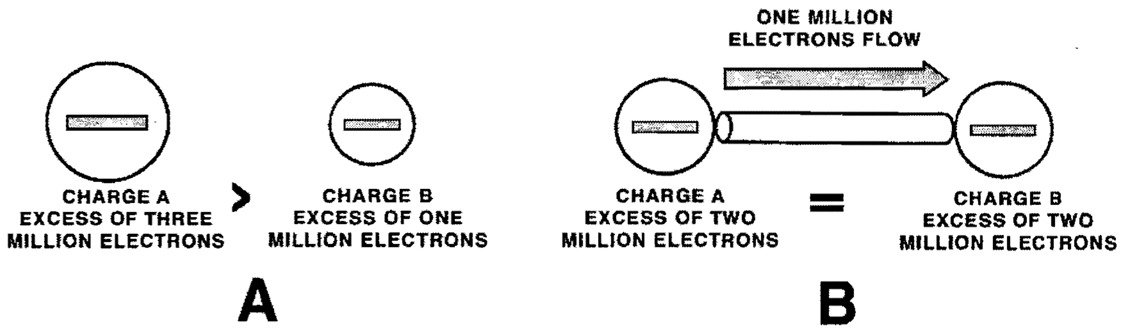

ONE MILLION ELECTRONS FLOW
CHARGE A EXCESS OF THREE MILLION ELECTRONS
>
CHARGE B EXCESS OF ONE MILLION ELECTRONS
CHARGE A EXCESS OF TWO MILLION ELECTRONS
=
CHARGE B EXCESS OF TWO MILLION ELECTRONS
A
B

Figure 2-4
A potential exists between two charges of the same polarity if they have different magnitudes.

Figure 2-5A illustrates two positive charges of different magnitudes. A potential exists here because electrons will flow if given the chance. Figure 2-5B shows a conductor connecting the two charges. Notice that electrons flow from the less positive (more negative) to the more positive potential. Again, the number of electrons which flow is the amount necessary to exactly balance the two charges.

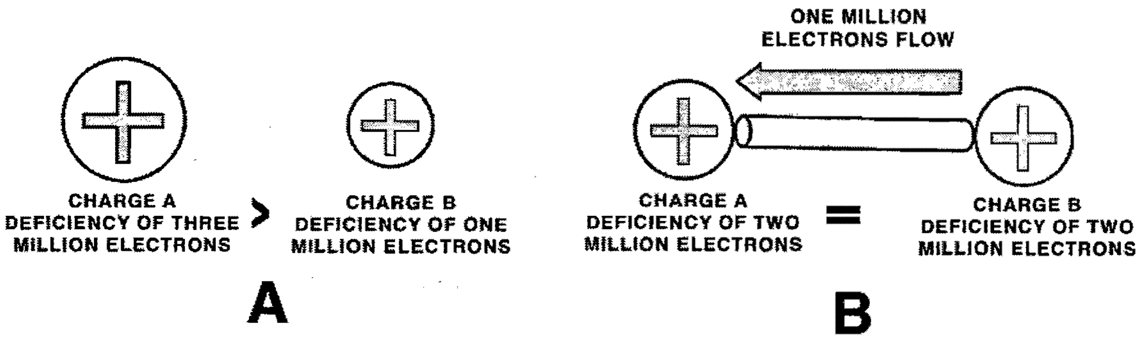

ONE MILLION ELECTRONS FLOW
CHARGE A DEFICIENCY OF THREE MILLION ELECTRONS
>
CHARGE B DEFICIENCY OF ONE MILLION ELECTRONS
CHARGE A DEFICIENCY OF TWO MILLION ELECTRONS
=
CHARGE B DEFICIENCY OF TWO MILLION ELECTRONS
A
B

Figure 2-5
Electrons flow from the less positive to the more positive charge.

Figure 2-6 shows five terminals at various levels of charge. Since no two are at the same charge level, a difference of potential exists between any two terminals. Consequently, if a conductor is placed between any two terminals, electrons will flow until those two charges are balanced. Notice that terminal C has no charge. That is, it contains the same number of electrons as positive ions. Nevertheless, if terminal C is connected to any other terminal, electrons will still flow. If it is connected to one of the negative terminals, electrons will flow into terminal C. If it is connected to one of the positive terminals, electrons will flow from terminal C. Remember that electrons always flow from the more negative to the more positive terminal.

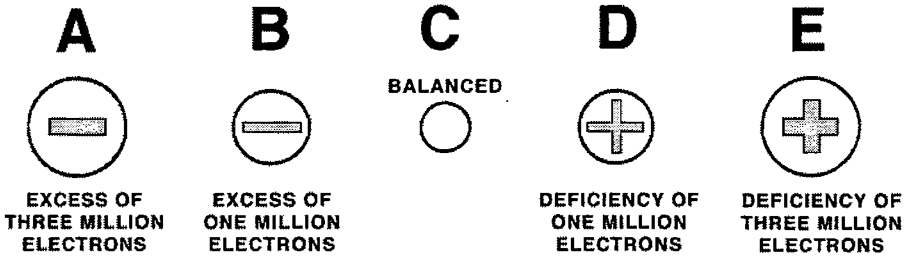

A
B
C
D
E
BALANCED
EXCESS OF THREE MILLION ELECTRONS
EXCESS OF ONE MILLION ELECTRONS
DEFICIENCY OF ONE MILLION ELECTRONS
DEFICIENCY OF THREE MILLION ELECTRONS

Figure 2-6
Five levels of charge.

Voltage

Another term which is often used interchangeably with emf and potential difference is *voltage*. However, strictly speaking there is a difference between voltage and emf. Voltage is the measure of emf or potential difference. For example, the battery in your car has an emf of 12 volts. The emf supplied by wall outlets is 115 volts while that required by most electric stoves is 220 volts. A large-screen color TV receiver produces an emf at one point which may be 25,000 volts or higher. High tension power lines often have a difference of potential as high as 500,000 volts.

The unit of emf or potential difference is the *volt*. At this point it is difficult to visualize exactly how much emf constitutes one volt. However, as you work with electronics, this point will become clearer. One volt is the magnitude of emf which causes one unit of energy or work to move one coulomb of charge from one point to another. The metric unit of energy or work is the *joule*. This unit is equally difficult to visualize since it is defined in other unfamiliar terms such as newtons. However, joules can be expressed in the more familiar English units. For example, one joule is equal to 0.738 foot-pounds. A foot-pound is the amount of work required to lift one pound one foot. Thus, a joule is approximately the amount of work required to lift 3/4 of a pound one foot off the ground.

Using this information, let's return to the volt. One volt is the emf required to cause one joule (or 0.738 foot pounds) of work to move one coulomb of charge (6.25×10^{18} electrons) from one point to another. To look at it another way, when movement of one coulomb of charge between two points produces one joule (or 0.738 foot-pounds) of work, the emf between the two points is 1 volt. Later on, after we have discussed resistance, we will define the volt in terms of current and resistance. It will then be much easier to visualize.

The abbreviation of volt is V. Thus, 1.5 volts is abbreviated 1.5V. As with amperes, metric prefixes are attached to indicate smaller and larger units of voltage. Thus, one millivolt equals 1/1000 volt, while one microvolt equals 1/1,000,000 volt. Also, one kilovolt equals 1000 volts while one megavolt equals 1,000,000 volts.

Programmed Review

1. A force or pressure exists between charges as a result of Coulomb's law. This law states that like charges repel and unlike charges attract. Electrons have a negative charge. Consequently, they are repelled by negative charges and are attracted by ____________ charges.

2. (positive) The force which causes electrons to move is given several names. One name is electromotive force and is abbreviated __________.

3. (emf) Although this is the force which causes electrons to move in a circuit, the force can exist without movement of electrons. For example, a battery which has been removed from a circuit still has an emf between its terminals. Therefore, you can think of emf as a potential for *producing* movement of electrons. Because of this, another name often given to emf is ____________ difference.

4. (potential) Often, the name *potential difference* is turned around and called a ____________ *of potential.*

5. (difference) A difference of potential exists between any two charges which are not exactly alike. Figure 2-6 shows five terminals each of which is at a different potential or state of charge. Terminal A has the most negative charge while terminal E has the most positive charge. Therefore, the greatest difference of potential exists between terminals A and ____________.

6. (E) If a conductor is connected from charge A to charge E, electrons will flow from A to E until both charges are neutralized. Therefore, ____________ electrons will flow from A to E.

7. (3,000,000) It is important to remember that even an uncharged body has a difference of potential with respect to a charged body. Thus, although terminal C is electrically neutral, it is more negative than terminals D or E. Also, terminal C is more positive than terminals ____________ and ____________.

8. (A, B) An emf exists between two unequal negative charges. For example, charge A is more negative than charge B. Or stated another way, charge B is more ____________ than charge A.

9. (positive) Consequently, if a conductor is connected from A to B, electrons will flow from the more negative terminal to the more positive terminal or from ____________ to ____________ .

10. (A, B) A difference in potential also exists between two unequal positive charges. For example, charges D and E are both positive but charge ____________ is more positive.

11. (E) An emf exists between these two charges. Emf is measured in volts. Thus, voltage is a measure of potential difference or ____________ .

12. (emf) A volt represents one joule of energy (or work) per coulomb of charge. Don't worry that this magnitude of emf is difficult to visualize. As you continue your study in the units that follow, you will develop a better understanding of this quantity. As you will see later, the volt has a very simple relationship to the ampere.

PRODUCING EMF

Emf is produced when an electron is forced from its orbit around the atom. An electric pressure exists between the free electron and the resulting positive ion. Thus, any form of energy which can dislodge electrons from atoms can be fused to produce an emf. In no case is energy actually created. It is simply changed to electrical energy from other forms. For example, a battery converts chemical energy to electrical energy, while a generator converts mechanical energy to electrical energy.

There are six common methods of producing emf, each with its own application. Let's briefly take a look at each of these.

Magnetism

This is the most important method of producing electrical power in the world today. At our present level of technology, it is the only method which can produce enough electrical power to run an entire city. Well over 99 percent of all electrical power is produced by this method.

The principle behind this technique is quite simple. When a conductor is moved through a magnetic field, an emf is produced. This is called *magnetoelectricity.* The force of the magnetic field and the movement of the conductor provide the energy necessary to free electrons in the conductor. If the conductor forms a closed loop, then the electrons will flow through the conductor.

The basic requirements are a magnetic field, a conductor, and relative motion between the two. Figure 2-7 shows a simple example. Here, the magnetic field is produced by a permanent magnet. The field is represented by the lines drawn from the north to south poles of the magnet. If a conductor is moved up so that it cuts the field as shown in Figure 2-7A, electrons will flow in the direction indicated. The same effect will be obtained if the conductor is held still and the magnet is moved down. All that is required is relative motion between the magnetic field and the conductor.

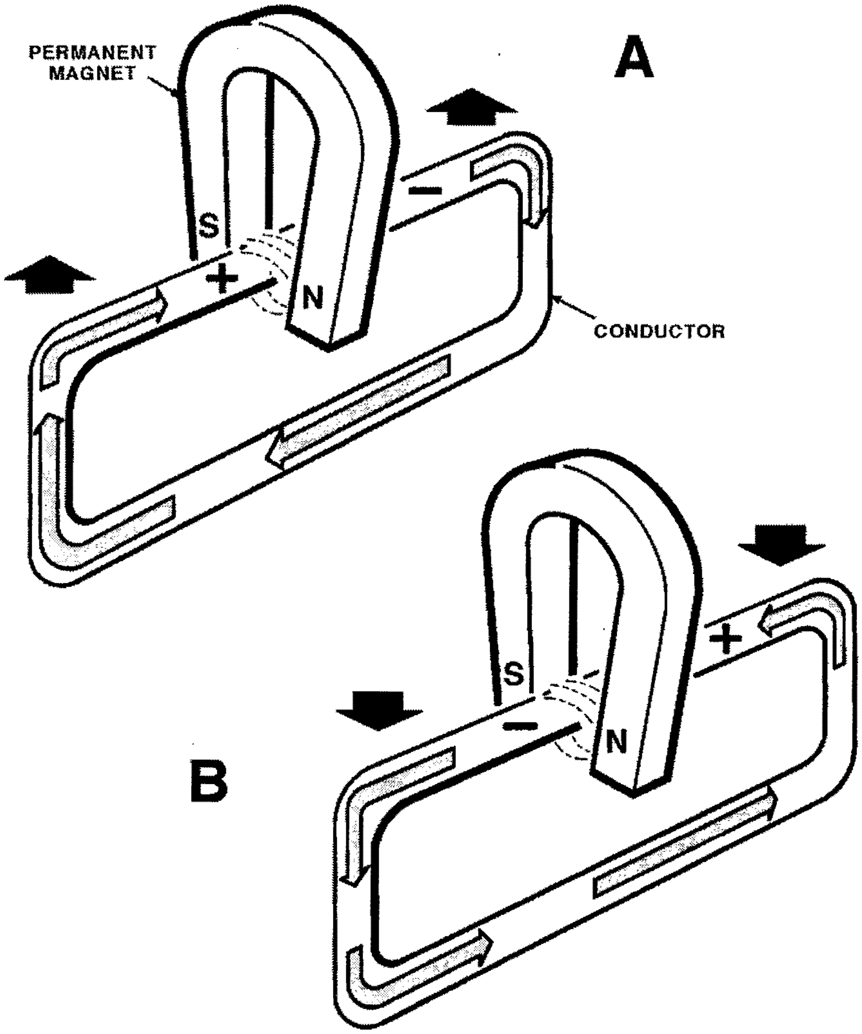


Figure 2-7
Electricity from magnetism.

Figure 2-7B shows that electrons flow in the opposite direction if the relative motion is reversed. If the conductor is moved up and down in the magnetic field, the electron flow reverses each time the motion reverses. In generators, a reciprocal motion like this is required. Thus, the current produced alternately flows in one direction then the other. This is known as alternating current or simply AC. In power generating stations the reciprocal motion occurs 60 times each second. Thus, the power supplied to our homes is often referred to as 60-cycle AC. This is an alternating current which goes through the forward-and-reverse current cycle 60 times each second. In this course, we are not concerned with alternating current although we will discuss magnetism in some detail later.

Chemical

The next most popular method of generating electricity is by chemical means, sometimes called *electrochemistry*. Automobile and flashlight batteries are examples of two typical applications. There are many chemical reactions that transfer electrons so that an emf is produced.

Figure 2-8 illustrates how a basic battery or cell can be made. A glass beaker is filled with a solution of sulfuric acid and water. This solution is called the *electrolyte*. In the electrolyte, the sulfuric acid breaks down into hydrogen and sulfate. Due to the chemical action involved, the hydrogen atoms give up electrons to the molecules of sulfate. Thus, the hydrogen atoms exist as positive ions while the sulfate molecules act as negative ions. Even so, the solution has no net charge since there are the same number of negative and positive charges.

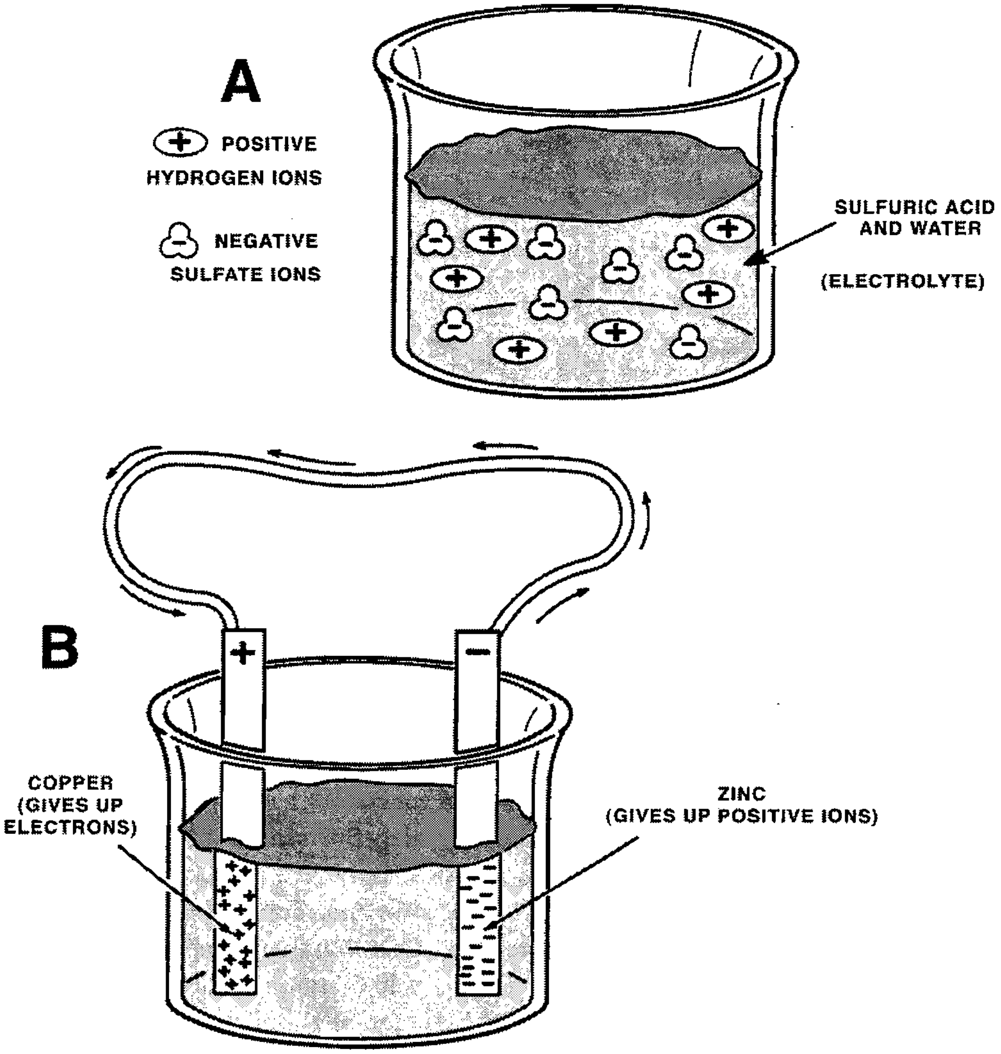
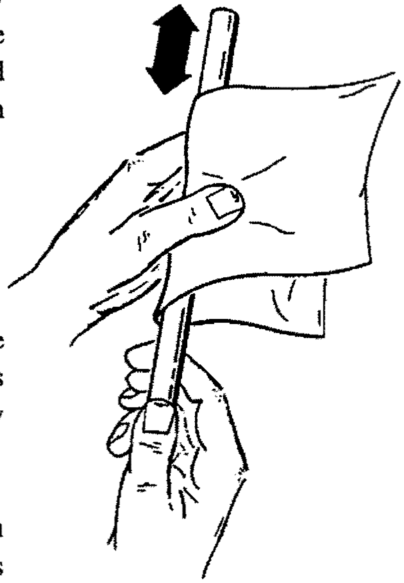

A
POSITIVE HYDROGEN IONS
NEGATIVE SULFATE IONS
SULFURIC ACID AND WATER
(ELECTROLYTE)
B
+
−
COPPER (GIVES UP ELECTRONS)
ZINC (GIVES UP POSITIVE IONS)

Figure 2-8
Electricity from chemicals.

Next, two bars called electrodes are inserted into the solution. One bar is copper while the other is zinc. The positive ions of hydrogen attract the free electrons in the copper. Thus, the copper bar gives up electrons to the electrolyte. This leaves the copper bar with a net positive charge.

The zinc reacts with the sulfate in much the same way. The sulfate molecules have a negative charge. Thus, positive zinc ions are pulled from the bar. This leaves the zinc bar with a surplus of electrons and a net negative charge.

If a conductor is connected between the zinc and copper bars, electrons will flow from the negative to the positive terminal. Because current flow is always in the same direction, we call this direct current or DC. Compare this to the AC voltage produced by magnetism in Figure 2-7. We will discuss somewhat more practical batteries in detail later in this unit.

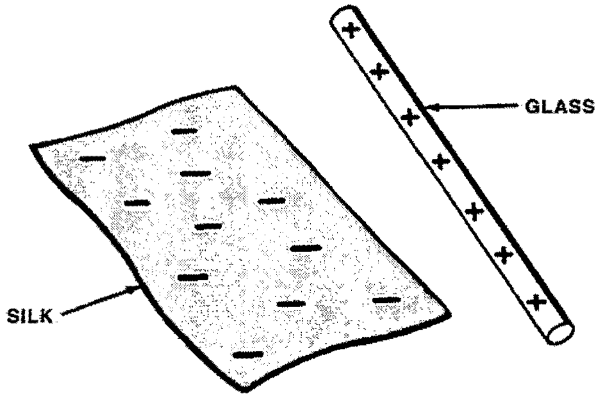


Friction

The oldest method known for producing electricity is by friction. We discussed some examples of this in the previous unit. Figure 2-9 shows that a rubber rod becomes negatively charged if it is rubbed with fur. Also, a glass rod becomes positively charged when it is rubbed with silk.

You have probably experienced this phenomenon yourself many times. When you scuff your feet across a nylon or wool rug, your shoes develop a charge which is transferred to the body. When you touch a neutral object such as a metal door knob or another person, a discharge occurs. Frequently, there is a tiny arc between your finger and the neutral body.

In many cases, static electricity produced by friction is troublesome or annoying. However, there is a device used in physics laboratories which uses this principle to develop very high voltages. It is called the Van de Graaff generator, and some models produce 10 million volts or more. Producing electricity from friction is called the *triboelectric effect.*



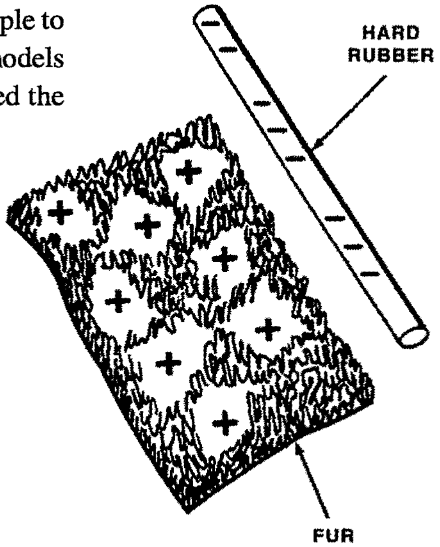


Figure 2-9
Electricity from friction.

Light

Light energy can be converted to electrical energy in large enough quantities to provide limited amounts of power. A familiar example of this is the solar cells frequently used on spacecraft. Although solar cells are still expensive, recent scientific advances have significantly reduced the cost. In fact, in the not-too-distant future, solar cells will probably be used for commercial purposes on a much larger scale.

Figure 2-10 shows the construction of one type of solar or photo cell. It consists of some type of photosensitive material sandwiched between two plates which act as electrodes. A photosensitive material is one which develops a charge when it is bombarded by light. Some substances which do this are cesium, selenium, germanium, cadmium, and sodium. When these materials are struck by light, some of the atoms release electrons. This is known as the *photoelectric effect.* In Figure 2-10, light passes through the translucent window and strikes the selenium alloy underneath. Some of the selenium atoms give up electrons and a charge is developed between the two plates. When a single cell is exposed to sunlight, it can provide a fraction of a volt charge and deliver a few milliamperes of current. When they are used as a power source, hundreds of the cells are tied together so that they produce usable voltage and current levels.

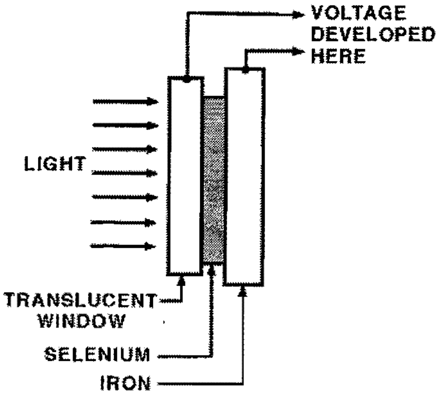


Figure 2-10
Electricity from light.

Pressure

A small electrical charge is developed in some materials when they are subjected to pressure or bending. This is referred to as the *piezoelectric effect.* Although present to a small degree in many different materials, it is especially noticeable in substances such as quartz, tourmatine, and Rochelle salts, all of which have a highly crystalline structure. Figure 2-11 illustrates how the charge is produced. In the normal structure, negative and positive charges are distributed so that no overall charge can be measured. However, when the material is subjected to pressure or bending, electrons leave one side of the material and accumulate on the other side. Thus, a charge is developed. When the pressure is relieved, the charges are again distributed so that the net charge disappears.

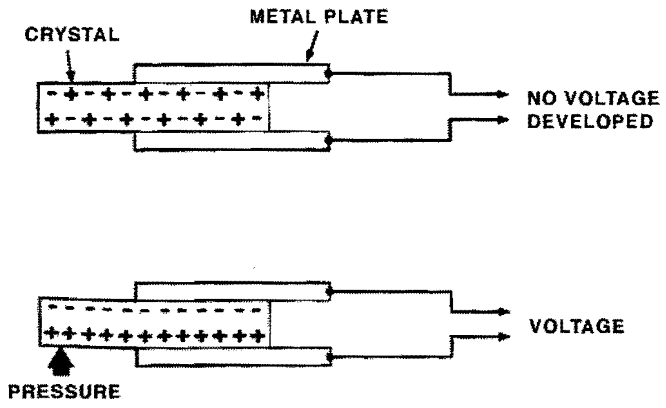


Figure 2-11
Electricity from pressure.

This effect is put to good use in devices such as crystal microphones and phonograph pickups, which actually convert mechanical vibration into a small, but amplifiable, electrical vibration (signal) based upon the piezoelectric effect. Also, in addition to these applications, the *reverse piezoelectric effect* by which electricity is converted into mechanical vibration, is applied in devices such as precision oscillators and speakers.

Heat

As with most other forms of energy, heat can be converted directly into electricity. The device for doing this is called a *thermocouple.* A thermocouple consists of two different or dissimilar metals joined together. A typical example is copper and zinc. You have seen that copper readily gives up electrons. This is especially true when the copper is heated. As shown in Figure 2-12, free electrons from the copper are transferred to the zinc. Thus, the copper develops a positive charge while the zinc develops a negative charge. Since more heat causes more electrons to transfer, the charge developed is directly proportional to the heat applied. This characteristic allows the thermocouple to be used as a thermometer in areas which are too hot for conventional thermometers. A specific voltage across the thermocouple corresponds to a specific temperature. Therefore, the voltage can be measured and compared to a chart to find the corresponding temperature. The process by which heat is converted directly to electricity is called *thermoelectric effect.*

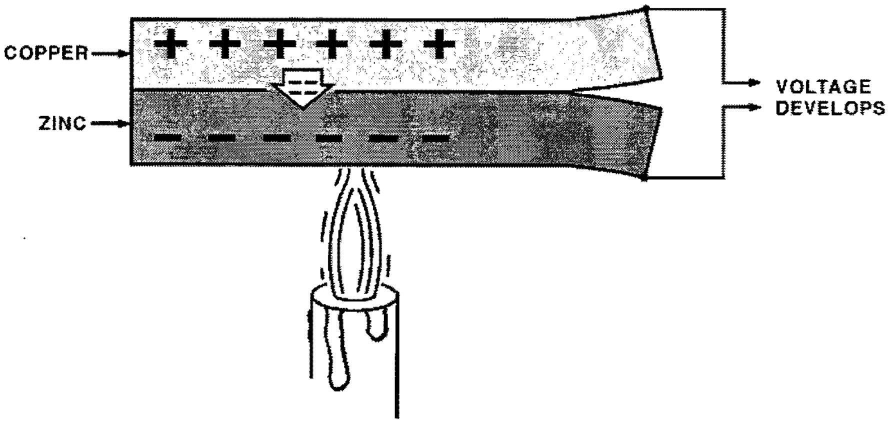


Figure 2-12
Electricity from heat.

Effects of Emf

You have seen that an emf can be produced by light, heat, magnetism, pressure, and chemical activity. It is interesting to note that the reverse is also true. That is, an emf can produce light, heat, magnetism, pressure, and chemical activity. The light bulb is an application of light produced by electricity. The toaster and electric stoves are examples where electricity is used to produce heat. When current flows through a wire, the wire is surrounded by a magnetic field. This magnetic field is put to practical use in motors, loudspeakers, and solenoids. Recall that a crystal produces a voltage when it is bent or twisted. However, when a voltage is applied to a crystal, the structure bends or twists. Thus, emf can produce pressure. Finally, emf can produce chemical activity. An example of this is the electrolysis of water. When an electric current flows through water, the water is broken down into its component parts of hydrogen and oxygen. Electroplating is another example of chemical activity caused by electricity.

Programmed Review

13. There are many methods of producing an emf or voltage. Generally, emf is produced as the result of one of six phenomenons or effects. These are:

Magnetoelectric
Electrochemical
Photoelectric
Triboelectric
Piezoelectric
Thermoelectric

Of these, the method used to produce electricity to run our factories and homes utilizes the ____________ effect.

14. (magnetoelectric) This effect produces an emf when a moving conductor cuts a magnetic field or when a moving magnetic field is cut by a conductor. Thus, in addition to a magnetic field and a conductor, there must be relative ____________ between the two.

15. (motion or movement) Batteries use a chemical reaction to produce emf. Two electrodes of different types of metals are placed in a solution which reacts with the metals. Electrons are pulled from one electrode to leave a positive charge, while positive ions are pulled from the other to leave a negative charge. The solution which reacts with the metal electrodes is called the ____________ .

16. (electrolyte) Another device which can produce an emf is the solar cell. It utilizes the ____________ effect to produce a voltage.

17. (photoelectric) The earliest known method of producing electricity is by friction. While this method has a few practical uses, electricity produced in this manner is usually a nuisance. It causes lightning, fires, and static on radio and TV. Electricity produced by ____________ is attributed to the triboelectric effect.

18. (friction) Certain materials produce an emf when they are subjected to a bending or twisting pressure. The crystal microphone and phonograph pickup use this effect. It is called the ___________effect.

19. (piezoelectric) Finally, a small voltage can be produced by the thermoelectric effect. The thermocouple works on this principle to produce an emf which is proportional to the temperature to which it is subjected. The thermocouple is nothing more than two pieces of dissimilar metals joined together. When heat is applied to the junction, a small emf is produced. Thus, the thermocouple converts ___________ to electricity.

20. (heat) Match each of the following applications of electricity with the effect which causes it:

	Application		Effect
1.	battery	A.	magnetoelectric
2.	generator	B.	piezoelectric
3.	crystal microphone	C.	thermoelectric
4.	thermocouple	D.	electrochemical
5.	solar cell	E.	photoelectric

21. (1-D, 2-A, 3-B, 4-C, 5-E) While the effects listed above can produce an emf, an emf can produce the effects. Match each of the following applications with the effect produced by the emf.

	Application		Effect
1.	flashlight	A.	heat
2.	automobile cigarette lighter	B.	chemical activity
3.	electroplating	C	light
4.	electromagnet	D.	pressure
5.	crystal earphones	E.	magnetism
6.	light bulb		
7.	toaster		
8.	motor		
9.	electrolysis of water		

22. (1-C, 2-A, 3-B, 4-E, 5-D, 6-C, 7-A, 8-E, 9-B)

BATTERIES

We discussed one type of battery or cell in the previous section. It consisted of zinc and copper electrodes inserted into an electrolyte of sulfuric acid and water. In this section we will discuss the construction and operation of several more common types of batteries. But first let's discuss the difference between a battery and a cell. A cell is a single unit which contains negative and positive electrodes separated by an electrolyte. A battery is a combination of two or more electrochemical cells. Thus, what we call a flashlight battery is really a cell since it contains only one unit for producing an emf. In spite of this technical definition the word battery is loosely used to describe a single cell.

There are two basic types of cells. One type can be *recharged* and is called a *secondary* cell. The other type can *not* be *recharged* and is called a *primary* cell. All cells and batteries store energy in a chemical form which can be released as electricity.

Dry Cell

Figure 2-13 shows five familiar sizes of dry cells, while Figure 2-14 shows the construction of a dry cell like the one used in a flashlight. The positive terminal is the steel top at the end of the carbon electrode. The negative terminal is the zinc can or container which holds the rest of the cell. A plastic jacket protects the zinc container and insulates the negative terminal from the positive terminal.

Energizer
Energizer
Energizer

Figure 2-13
Five popular sizes of dry sell batteries.
(Photo courtesy of RCA.)

Even though this type of cell is referred to as a "dry cell," it is not dry on the inside but contains a moist paste. A wax seals off the open end of the zinc container. This prevents any paste from oozing out when the battery is turned upside down or placed on its side. Thus, this type of cell can be used in any position without the electrolyte escaping.

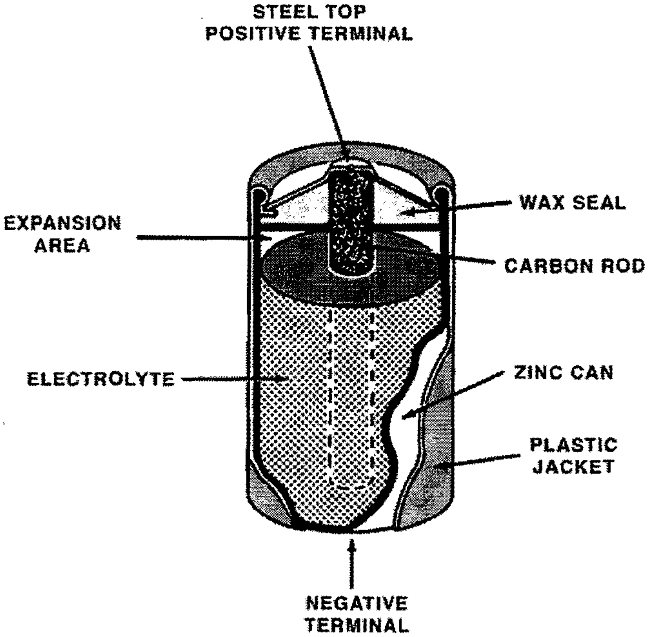


Figure 2-14

Construction of a dry cell.

The electrolyte used in this cell is a solution of ammonium chloride and zinc chloride. The electrolyte gradually dissolves the zinc by pulling away positive ions. This process leaves behind an excess of electrons. Thus, the remaining zinc acts as the negative electrode. If it were not for the carbon rod, the electrolyte would develop a positive charge by virtue of the positive ions pulled from the zinc. However, the positive charge is neutralized by electrons pulled from the carbon rod. Thus, the carbon rod has a deficiency of electrons which causes a positive charge.

This type of cell is referred to as the Leclanché cell and it produces just over 1.5 volts when new. As it is used, the chemical action slows and the voltage gradually decreases. This type of cell cannot be recharged so it is considered a primary cell. Also, because the paste gradually dries out, the dry cell slowly loses its ability to produce an emf. This occurs even if the battery is not in use. For this reason, the dry cell must be used within about two years of the time it is manufactured. That is, it has a shelf life of about two years.

The voltage delivered by this type of cell is determined strictly by the types of material used as the electrodes and the electrolyte. Thus, the voltage is determined by the chemical reaction and not the size of the cell. For this reason, a small pen light cell produces the same voltage as the much larger D cell. However, the larger battery has a higher current rating. The size D cell can deliver 50 milliamperes of current for approximately 60 hours. A small penlight cell becomes exhausted much sooner at the same current.

Lead-Acid Battery

The primary disadvantage of the dry cell is that it cannot be recharged. Other cells, called secondary cells, can be recharged. The most popular of the secondary cells is the lead-acid battery. In this type of cell, a reversible chemical reaction takes place. It is this reaction that produces emf between the battery terminals. Let's look at this reaction more closely.

In Figure 2-15A you see a typical lead-acid Battery. The positive electrode consists of a plate of lead dioxide (PbO_2) and the negative electrode is a plate of spongy lead (Pb). These are submersed in a solution of sulfuric acid (H_2SO_4) and water (H_2O).

The sulfuric acid in the solution separates into positive hydrogen ions (H^+) and negative sulfate ($S04^{--}$) ions. While this is happening, the lead plate begins to give up electrons and form Pb^{++} ions. Some of the negative sulfate ions in the solution combine with the positive lead ions on the surface of the negative electrode and form a coating of lead sulfate. The electrons given up by the lead plate will travel through the conductor to the positive electrode.

Meanwhile, the atoms on the surface of the lead dioxide plate give up negatively charged oxygen ions (O^{--}) into the solution. The loss of the electrons which the oxygen carries into the solution gives the lead dioxide plate an overall positive charge. That is, Pb^{++++} ions are formed on the surface of the plate. Again, as with the negative electrode, some of the negative sulfate ions combine with the positive lead ions to form a coating of lead sulfate on the positive electrode. However, this does not completely neutralize the charge of the lead ions. In fact, each of the lead ions on the plate is still Pb^{++}. It is this positive charge that attracts the electrons from the negative electrode through the conductor.

The negatively charged oxygen ions in the solution now combine with the positively charged hydrogen ions, which resulted from the separation of the sulfuric acid, and form water (H_2O). As the cell discharges, the amount of water increases while the amount of acid decreases.

This entire process can be reversed by reversing the ion flow through the battery. You can do this by connecting a source of dc voltage greater than that produced by the lead-acid cell as shown in Figure 2-15B. However, during the recharging process, some of the hydrogen in the solution will escape into the air. Since hydrogen in its pure form is highly explosive, you should be extremely careful when charging a lead-acid battery.

The amount of emf produced by a cell is determined by the chemical reaction that occurs within the cell. The lead-acid cell just described produces an emf of about 2.1 volts. Cells made of other materials will produce different voltages.

The amount of current that a cell can deliver is determined by the size of the cell or, to state it more correctly, by the physical size of the electrodes and the amount of sulfuric acid in the solution.

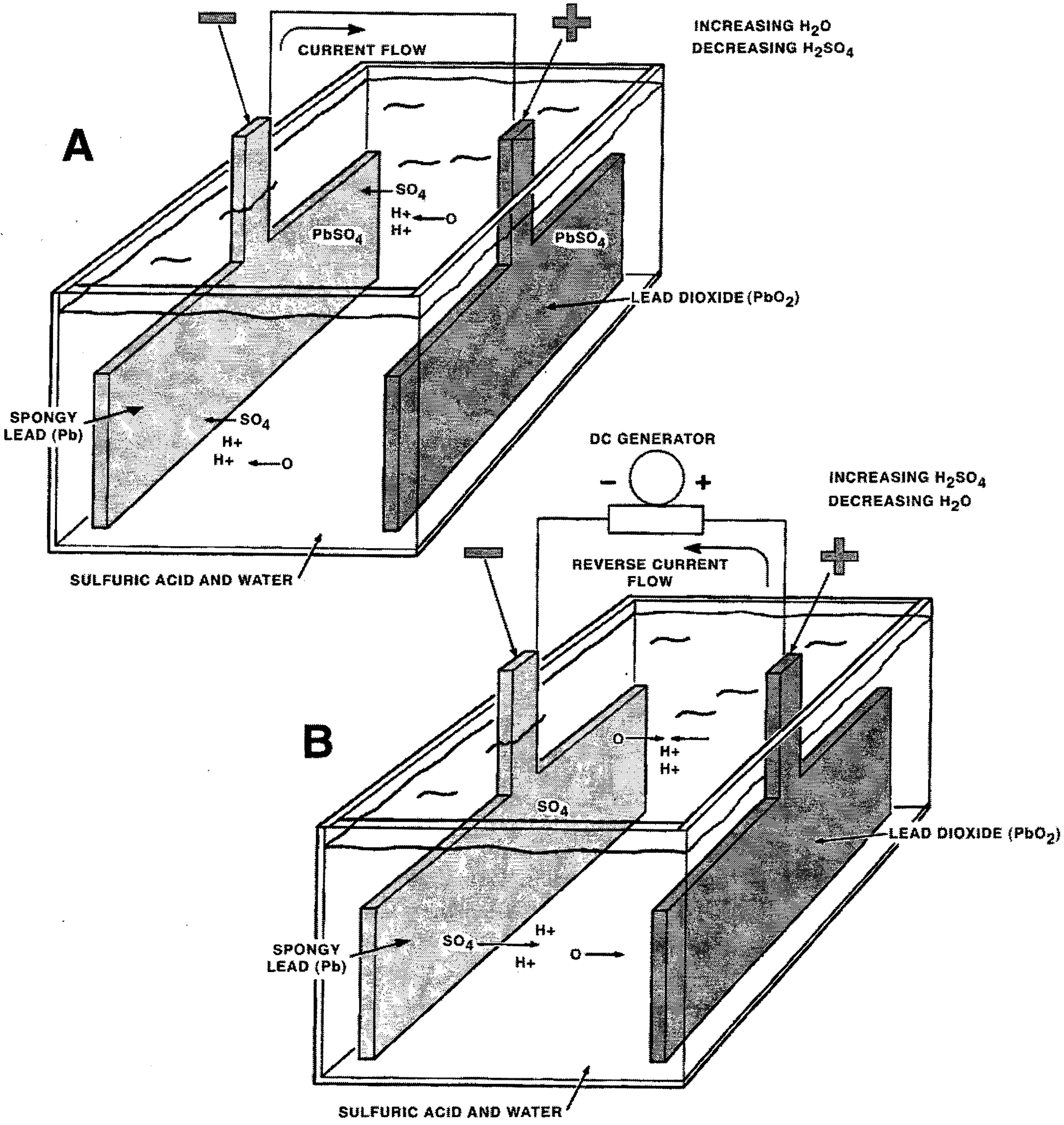

A
CURRENT FLOW
INCREASING H_2O
DECREASING H_2SO_4
SO_4
H+
H+
O
$PbSO_4$
$PbSO_4$
LEAD DIOXIDE (PbO_2)
SPONGY LEAD (Pb)
SO_4
H+
H+
O
SULFURIC ACID AND WATER
B
DC GENERATOR
INCREASING H_2SO_4
DECREASING H_2O
REVERSE CURRENT FLOW
O
H+
H+
SO_4
LEAD DIOXIDE (PbO_2)
SPONGY LEAD (Pb)
SO_4
H+
H+
O
SULFURIC ACID AND WATER

Figure 2-15
The basic lead-acid cell.

Programmed Review

23. A cell or battery is a device which stores energy in chemical form. However, the energy is released in an ____________ form.

24. (electrical) Technically, there is a difference between a battery and a cell. A cell is a single unit consisting of two electrodes separated by an electrolyte. A battery is composed of two or more ____________ connected together for a specific current and voltage rating.

25. (cells) The main parts of a cell are its two electrodes and an ____________ which separates them.

26. (electrolyte) There are two types of cells. A primary cell is one that cannot be recharged. A secondary cell is one that can be ____________ .

27. (recharged) The dry cell is a primary cell. It has a carbon rod for a positive electrode and the zinc container acts as the negative electrode. An acid solution of ammonium chloride and zinc chloride is used as the ____________ .

28. (electrolyte) When new, the dry cell produces an emf of about ____________ volts.

29. (1.5) The lead-acid cell is a secondary cell because it can be recharged again and again. The electrolyte is a mixture of sulfuric acid and water. The positive plate is lead dioxide while the negative plate is pure ____________ .

30. (lead) The electrolyte converts the lead to lead-sulfate and in the process creates negative and positive charges. This type of cell produces an emf of approximately ____________ volts.

31. (2.1) To recharge the cell, a voltage of about 2.5 volts is placed across the cell to force current through it in the opposite direction. This reverses the chemical reaction and converts the lead-sulfate back to ____________ acid.

32. (sulfuric) The lead-acid cell is called a wet cell because the electrolyte is a liquid. For this reason it should not be turned on its side or upside down. This contrasts with the ____________ cell which can be used in any position.

33. (dry) The battery used in most automobiles consists of a number of lead-acid cells connected together so that the voltage from the individual cells add together. Since the output voltage of a single cell is about 2.1 volts, a battery having an emf of 6.3 volts must consist of ____________ cells.

34. (three) In the same way, a 12.6 volt battery must consist of ____________ cells connected so that the voltages add.

35. (six)

CONNECTING BATTERIES

We have seen that cells can be connected together to increase the voltage or current rating. There are four different ways that cells or batteries can be connected. These are series-aiding, series-opposing, parallel, and series-parallel. Let's examine each of these methods in detail.

Series-Aiding Connection

In the 12-volt automobile battery six cells are connected together so that the individual cell voltages add together. In the 6-volt battery, three cells are connected in the same way. This arrangement is called a *series-aiding* connection and is shown in Figure 2-16A as it occurs in a three-cell flashlight. The cells are connected so that the positive terminal of the first connects to the negative terminal of the second; the positive terminal of the second connects to the negative terminal of the third; etc. This is a series connection because the same current flows through all three cells. It is an aiding connection because the voltages add together. Since the individual emf of each cell is 1.5 volts, the overall emf is 4.5 volts. The schematic diagram for this connection is shown on the right.

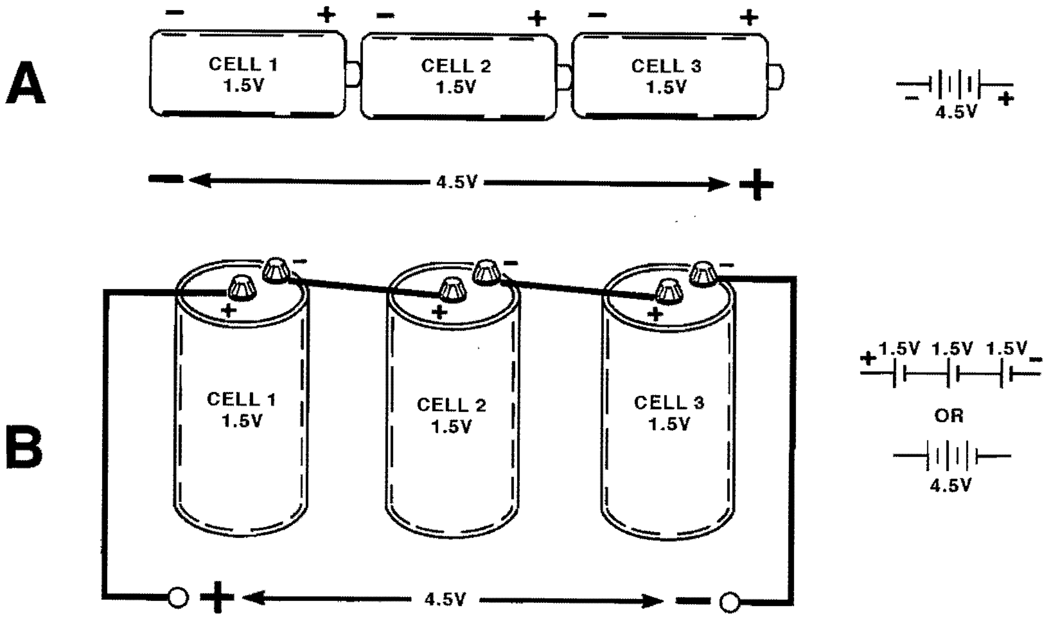


Figure 2-16
The series-aiding connection

Figure 2-16B shows a different type of cell. Here again the three cells are wired together in series. Notice that the voltages add together because between cells the opposite polarity terminals are connected. That is, the negative terminal of the first cell connects to the positive terminal of the next and so on. Thus, the three 1.5-volt cells provide a total emf of 4.5 volts. The schematic symbol is shown on the right.

With the series-aiding connection, the total voltage across the battery is equal to the sum of the individual values of each cell. However, the current capacity of the battery does not increase. Since the total circuit current flows through each cell, the current capacity is the same as for one cell.

Series-Opposing Connection

The series-aiding connection just discussed is extremely important and is widely used. The *series-opposing* connection of cells is just the opposite. It has little practical use and is usually avoided. It is mentioned here to complete your understanding of battery connections. The series opposing connection of two cells is shown in Figure 2-17A. Notice that the two cells are connected in series, but *like* terminals of the cells are connected together. Here the two voltages cancel each other so that the overall emf is 0 volts. Because the two voltages cancel, this arrangement cannot produce current flow.

Figure 2-17B shows another example of a series-opposing connection. Here, three cells are connected in series but cell number 2 is connected backwards. Consequently, its voltage is subtracted from the voltage of the two cells that are connected in series-aiding. The total voltage for cells 1 and 2 is 0 volts. This leaves the output voltage of cell 3. Therefore, the total output of the three cells is only 1.5 volts.

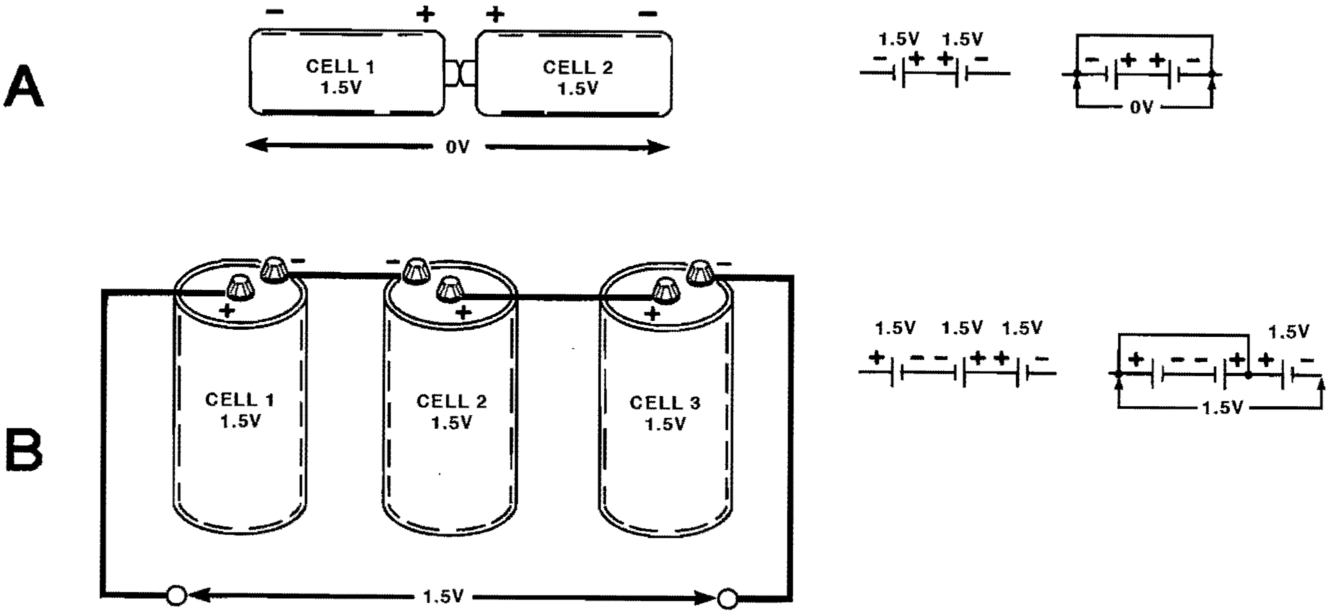


Figure 2-17

The series-opposing connection.

Notice in each of the series-opposing circuits shown that the two opposing batteries do not contribute to the overall voltage. Also notice that the opposing batteries are the *same* voltage. From this you may conclude that series-opposing batteries with identical voltages act like **a short** in a circuit. This is shown in the figure.

Parallel Connection

We have seen that the series-aiding connection of cells increases the output voltage but not the current capabilities of the cells. However, there is a way to connect cells so that their current capabilities add together. This is called a parallel connection and is shown in Figure 2-18A. Here, like terminals are connected. That is, all the positive terminals are connected together as are all the negative terminals.

Figure 2-18B shows why the current capacities of the cells are added together. Notice that the total current through the lamp is the sum of the individual cell currents. Each cell provides only one third of the total current. Thus, the total current capacity is three times that of any one cell. However, connecting the cells in this way does not increase the voltage. That is, the total voltage is the same as that for any one cell. If 1.5-volt cells are used, then the total voltage is 1.5 volts.

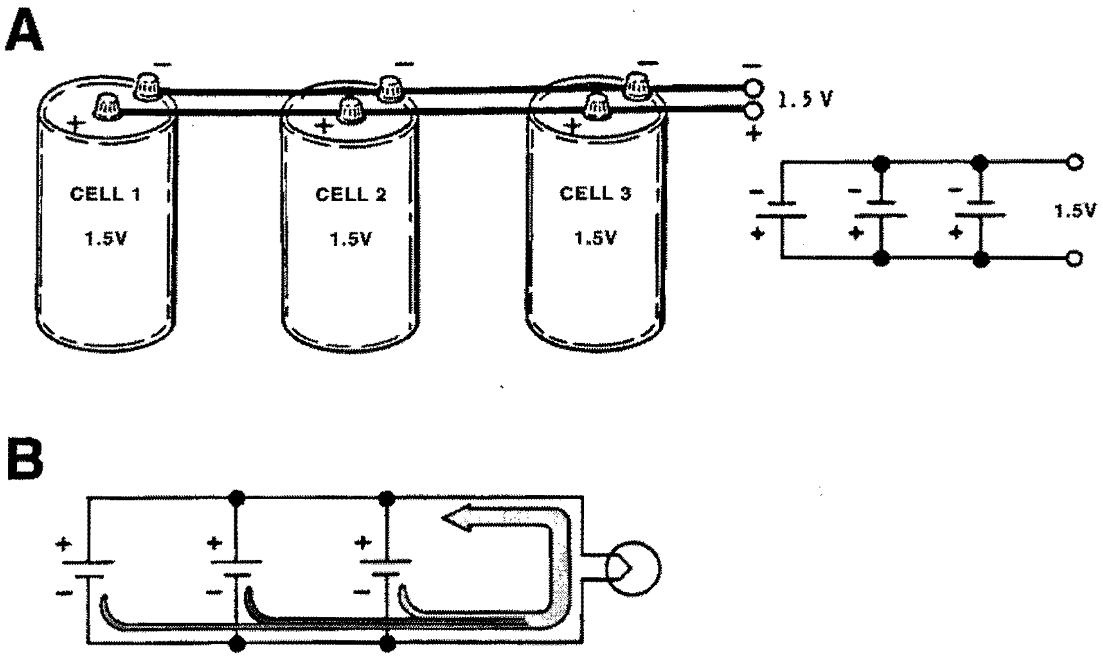


Figure 2-18
The parallel connection.

Series-Parallel Connection

When both a higher voltage and an increased current capacity are required, the cells are connected in series-parallel. For example, suppose we have four 1.5-volt cells and we wish to connect them so that the emf is 3 volts and the current capacity is twice that of any one cell. We can achieve this by connecting the four cells as shown in Figure 2-19. To achieve 3 volts, cells 1 and 2 are connected in series. However, this does not increase the current capacity. To double the current capacity we must connect a second series string (cells 3 and 4) in parallel with the first. The result is the series-parallel arrangement shown.

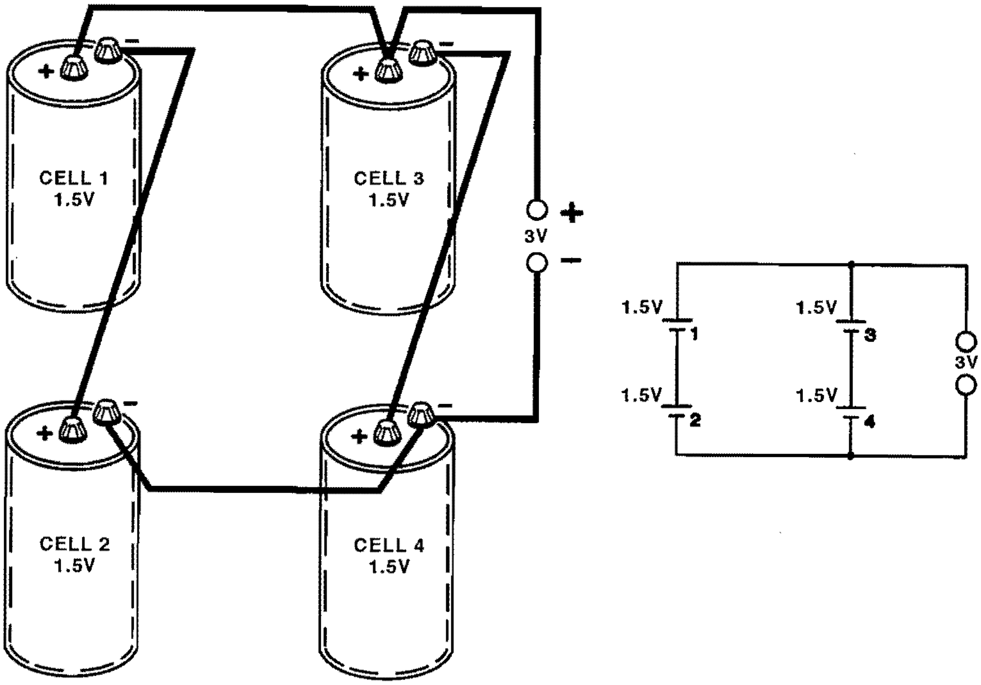


Figure 2-19

The series-parallel connection.

To be certain that you have the idea, let's consider another example. Let's suppose that we have a number of identical 1.5 volt cells from which we wish to construct a battery with an emf of 4.5 volts and current capacity three times that of the individual cells. Figure 2-20 shows that nine cells are required. Cells 1, 2, and 3 are connected in a series string to provide 4.5 volts. However, to achieve the higher current, three of these strings must be connected in parallel.

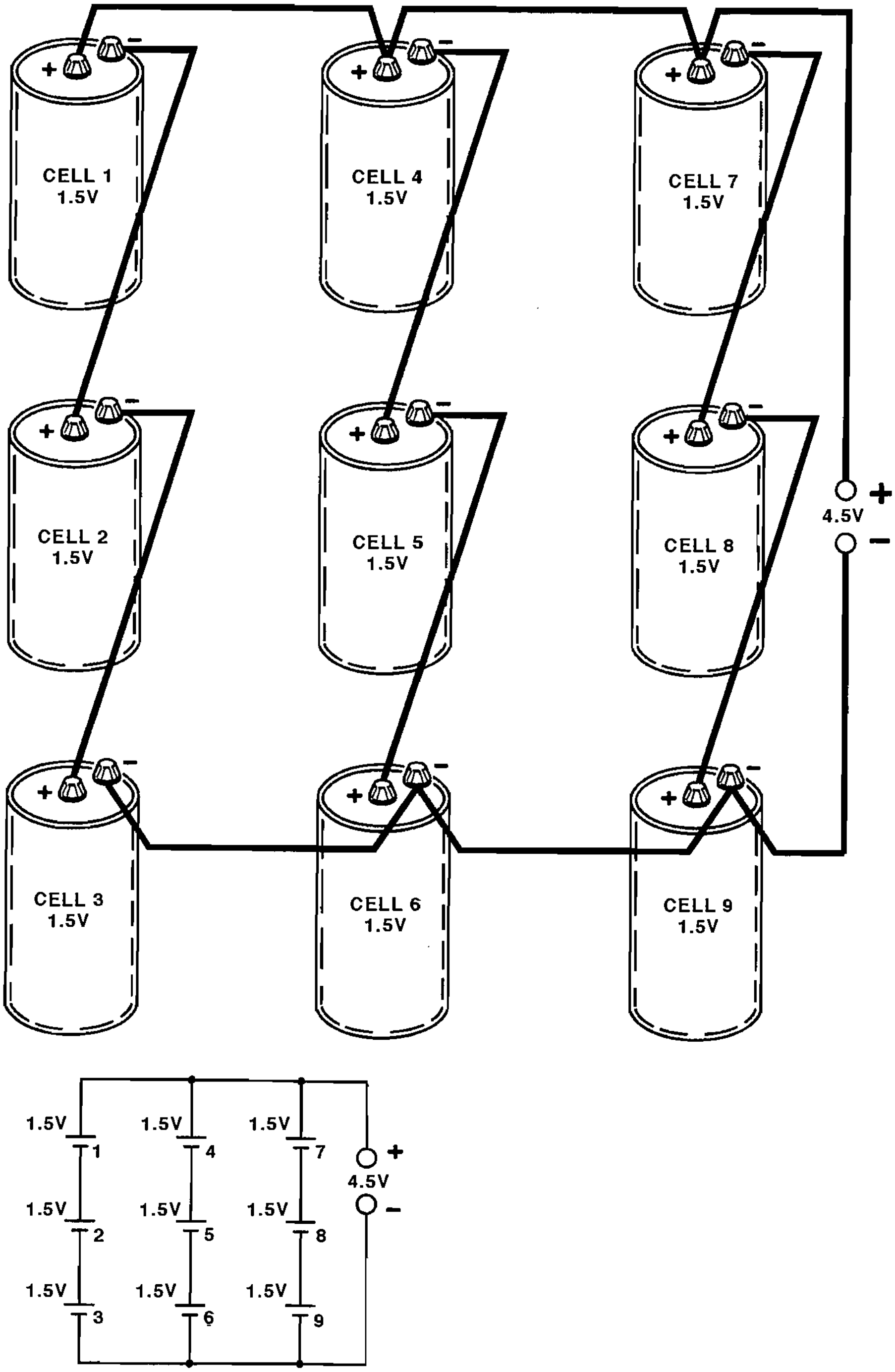

+
-
CELL 1
1.5V
CELL 2
1.5V
CELL 3
1.5V
CELL 4
1.5V
CELL 5
1.5V
CELL 6
1.5V
CELL 7
1.5V
CELL 8
1.5V
CELL 9
1.5V
4.5V
+
-
1.5V
1
1.5V
2
1.5V
3
1.5V
4
1.5V
5
1.5V
6
1.5V
7
1.5V
8
1.5V
9
4.5V
+
-

Figure 2-20

Nine cells connected in series-parallel.

Programmed Review

36. There are several different ways in which cells and batteries can be connected to-obtain a variety of voltages and current capacities. For example, when cells are connected in series-aiding, the voltages add. Thus, four cells each having an emf of 2.1 volts can be connected in a series -aiding configuration to produce an emf of ___________ volts.

37. (8.4) However, the series-aiding connection does not increase the current capacity because the total current must flow through all cells. When wiring cells in the series-aiding connection, the negative terminal of one cell is connected to the ___________ terminal of the next.

38. (positive) If three 1.5V batteries with a maximum current capacity of 100 milliamperes are connected series-aiding, the resulting battery will have an emf of ___________ volts and a current capacity of ___________ milliamperes.

39. (4.5,100) When connecting batteries, we sometimes inadvertently connect one battery backwards, or series-opposing. When this happens, the backwards battery actually subtracts from the circuit voltage. Consequently, if in a series string of four 1.5-volt batteries one battery is connected backwards, the total circuit voltage will be 1.5V + 1.5V + 1.5V – 1.5V = _________ volts.

40. (3.0) Notice that the backwards cell does not contribute to the circuit voltage. In fact, it actually subtracts from it. Thus, if two identical batteries are connected series-opposing, the output voltage will be ___________ volts.

41. (0) To increase the current capacity, cells are connected in parallel. Thus, if a single cell has a current capacity of 1/4 amp, then three of the cells in parallel will have a capacity of ___________ amp.

42. (3/4) However, connecting cells in parallel does not increase the voltage. If five 2.1-volt cells are connected in parallel, the total output voltage is ____________ volts.

43. (2.1) When we wish to increase both the voltage and the current, we connect the cells in a series-parallel connection. The voltage is determined by the number of cells in each series string of cells. The current capacity is determined by the ____________ of series strings connected in parallel.

44. (number) For example, suppose we have a number of identical 1.5 volt cells each with a current capacity of 200 milliamperes. To construct a 7.5 volt battery, we would require ____________ cells connected in ____________ .

45. (five, series) To obtain a current capacity of 800 milliamperes, we would have to connect ____________ of these strings in parallel.

46. (4) Therefore, a total of ____________ cells are required.

47. (20)

VOLTAGE RISES AND VOLTAGE DROPS

In electronics and electrical work, there are two kinds of emf or potential difference. Both are expressed in volts but they have somewhat different characteristics. One type of emf is called a voltage rise. The other is called a voltage drop. Let's take a look at the voltage rise first.

Voltage Rise

We have seen that a battery provides an emf or voltage. It does this by chemically producing an excess of electrons at the negative terminal and an excess of positive ions at the positive terminal. When a load is connected across the battery, electrons flow through the load. Each electron which leaves the negative terminal is replaced by an electron from the battery. At the positive terminal each electron arriving from the load cancels one positive ion. However, for each ion that is cancelled, the battery produces a replacement ion. Thus, the voltage between the two terminals remains constant even though electrons are constantly flowing from the negative terminal and into the positive terminal.

Energy is required to move the electrons through the load. The battery gives each electron the energy required to make the trip. We have seen that the energy (in joules) is related to the emf of the battery (in volts) and the number of electrons moved (in coulombs).

The energy comes from the chemical reaction within the battery. This energy has a capacity to do work and the amount of work is determined by the voltage of the battery. After all, it is the emf or voltage of the battery which causes the electrons to flow in the first place. The battery is a source of emf. This type of emf is referred to as a voltage rise. Thus, in an electrical circuit a voltage rise is an emf which is provided by a voltage source.

Earlier, we discussed several different types of voltage sources. The two most common are the generator and the battery. However, solar cells and thermocouples also produce an emf so they are considered voltage sources. Any emf introduced into a circuit by a voltage source is called a *voltage rise.* Thus, a 10-volt battery has a *voltage rise* of ten volts.

Voltage Drop

Electrons which leave the negative terminal of a battery have been given energy by the battery. As the electrons flow through the load, they give up their energy to the load. Most often the energy is given up as heat. However, if the load is a light bulb, both heat and light are given off. The point is that the electrons release to the circuit the energy given to them by the battery.

Since the energy introduced into the circuit is called a voltage rise, the energy removed from the circuit by the load is called a *voltage drop*. A voltage drop is expressed in volts just as with the voltage rise. In fact, the same equation expresses the relationship between volts, joules, and coulombs in both cases. The equation is:

$$\text{volts} = \frac{\text{joules}}{\text{coulombs}}$$

Using this equation, we can determine the voltage drop across a load if we know the energy consumed by the load (in joules) and the number of electrons flowing through the load (in coulombs). For example, let's assume that a light bulb releases 10 joules of energy in one second when a current of two amperes flows through it. With a current of two amperes, two coulombs flow through the bulb each second. Using the above equation, we can determine the voltage drop:

$$\text{volts} = \frac{\text{joules}}{\text{coulombs}}$$

$$\text{volts} = \frac{10 \text{ joules}}{2 \text{ coulombs}}$$

$$\text{volts} = 5$$

Thus, the voltage drop of the light bulb is 5 volts. It is important to realize that this voltage exists between the two terminals of the bulb and it can be measured by a meter. In fact, the meter cannot tell the difference between a voltage rise produced by a battery and a voltage drop produced by a load. This is the reason that a battery and a light bulb may both have a rating of 12 volts. In the case of the battery, it means that the battery supplies 12 volts. This is a voltage rise. However, for the light bulb, it means that 12 volts is required to make it work. This is a voltage drop.

One difference between the voltage drop and the voltage rise is that the voltage drop occurs only when current flows through the load. Thus, a battery has a voltage rise whether or not it is connected to a circuit. However, a load produces a voltage drop only when current flows through it.

Voltage Drops Equal Voltage Rises

Figure 2-21A shows a 10-volt battery with a light bulb connected across it. The battery provides a voltage rise of 10 volts. As electrons flow through the lamp, a voltage drop is developed across it. Since the lamp consumes the same amount of energy that the battery provides, the voltage drop across the lamp is equal to the voltage rise across the battery. That is, the voltage drop is 10 volts.

In Figure 2-21B, two light bulbs are connected in series across a 10-volt battery. Each bulb drops part of the 10 volts supplied. If the two lamps are identical, each will drop half of the supplied voltage as shown. If the two lamps are not identical, one bulb will drop more voltage than the other. However, the sum of the voltage drops will always equal the sum of the voltage rises.

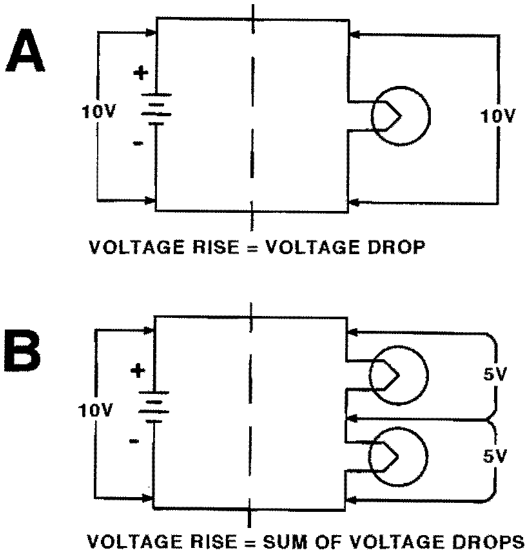

A
+
10V
-
10V
VOLTAGE RISE = VOLTAGE DROP
B
+
10V
-
5V
5V
VOLTAGE RISE = SUM OF VOLTAGE DROPS

Figure 2-21
The voltage drops
are equal to the voltage rises.

To be certain you have the idea, consider the example shown in Figure 2-22A. Here, three batteries are connected series-aiding across a single lamp. The sum of the voltage rises is equal to 12 volts. Hence the lamp must drop 12 volts. A final example is shown in Figure 2-22B. Here two 4.5-volt batteries are connected in series with three identical lamps. The total voltage rise in the circuit is 9 volts. Since the lamps are identical, each drops one third of the applied voltage, or 3 volts. Notice that once again, the sum of the voltage rises equals the sum of the voltage drops.

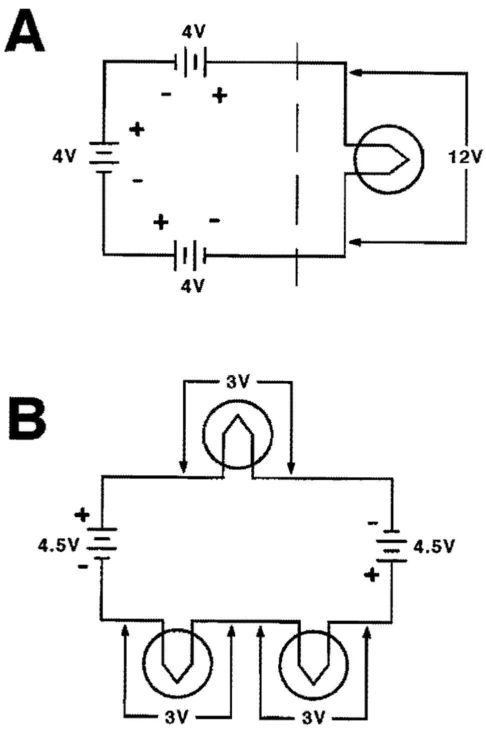


Figure 2-22
The sum of the voltage drops equals the sum of the voltage rises.

Programmed Review

48. In any circuit in which current flows, there are two types of emf. One is called a voltage rise. The other is called a voltage ____________ .

49. (drop) The voltage rise is provided by a voltage source such as a battery, a generator, a solar cell, or a thermocouple. In fact any device which produces emf is a voltage source and can provide a voltage ____________.

50. (rise) The voltage rise is present across a voltage source whether or not the source is connected to a circuit. For example, a 12-volt battery has a voltage rise of 12 volts whether or not current is flowing through it. As with all forms of emf the voltage rise is measured in ____________ .

51. (volts) The other form of emf is the voltage drop. Unlike the voltage rise, a voltage drop is present across a load only when ____________ flows through the load..

52. (current) Since current flow is caused by a voltage rise, a voltage drop cannot exist unless there is an accompanying voltage ____________ .

53. (rise) In a circuit in which current is flowing, the sum of the voltage drops equals the sum of the voltage rises. If the voltage rise in a circuit is 10 volts, the voltage drop will also be ____________ volts.

54. (10) If the load connected across a 10-volt battery is two lamps, each lamp will have a voltage drop. However, the sum of the two voltage drops must equal ____________ volts.

55. (10) If the two lamps are identical each will drop ____________ of the applied voltage.

56. (one-half)

CONCEPT OF GROUND

One of the most important points in the study of electricity and electronics is the concept of *ground.* Originally ground was just what the name implies—the earth. In fact, in some countries the name *earth is* used instead of *ground.* Earth is considered to have zero potential. Thus, ground, or earth, is the reference point to which voltages are most often compared. Many electrical appliances in your home are grounded. This is especially true of air conditioning units, electric clothes dryers, and washing machines. Often this is done by connecting a heavy wire directly to a cold water pipe which is buried deep in the earth (ground). In other cases, a third prong on the power plug connects the metal frame to ground. The purpose of this is to protect the user in case a short circuit develops in the appliance. It also places the metal parts of different appliances at the same potential so that you are not shocked by a difference in potential between two appliances. This type of ground is sometimes called *earth ground.*

However, there is a slightly different type of ground used in electronics. For example, a certain point in a small transistor radio is called *ground* although the radio does not connect to earth in any way. This is the concept of ground with which we will be primarily concerned in this course. In this case, **ground is simply a zero volt reference point within an electric circuit.** In most larger pieces of electronic equipment, the zero reference point or ground point is the metal frame or chassis on which the various circuits are constructed. All voltages are measured with respect to this chassis.

In your automobile, the chassis or metal body of the automobile is considered ground. If you look closely at the straps leaving the battery you will see that one wire connects directly to the metal frame of the car. This point is considered to be ground as is every other point on the metal frame.

In electronics, ground is important because it allows us to have both negative and positive voltage. Up to now we have been concerned only with relative voltages between two points. For example, a 6-volt battery has an emf between its two terminals of 6 volts. We do not think of this as +6 volts or –6 volts, but rather simply 6 volts.

However, the concept of ground allows us to express negative and positive voltages. Remember ground is merely a reference point which is considered zero volts or neutral. If we assume that the positive terminal of a 6-volt battery is ground, then the negative terminal is 6 volts *more* negative. Thus, the voltage at this terminal with respect to ground is –6 (negative 6) volts.

On the other hand, if we assume that the negative terminal of the battery is ground, then the positive terminal with respect to ground is +6 (positive 6) volts. Notice that the battery can produce –6 volts or +6 volts depending upon which terminal we call ground.

Many small electronic devices such as calculators, transistor radios, etc. do not have metal frames. Instead, all components are mounted on a printed circuit board. Here, ground is nothing more than an area of copper on the board. However, as before, all voltages are measured with respect to this point. In this case, ground is simply a common reference which is a specified starting point for measuring voltages.

The most widely used schematic symbol for ground is shown in Figure 2-23A. Other symbols are shown in Figure 2-23B. Figure 2-23C shows how the ground symbol is used in the circuit. Point A is at ground or zero potential. Now, since this is a 10-volt battery, point B is at a plus 10-volt potential with respect to ground. We say that point B is ten volts above ground or that the voltage at this point with respect to ground is +10 volts.

Figure 2-23D shows why ground is so important. Here, the same battery is shown, but with the positive terminal connected to ground. That is, the positive terminal is the zero volt point in this circuit. Because the negative terminal is ten volts more negative, the voltage at point A with respect to ground is –10 volts. Thus, we can use the battery as a +10-volt source or as a –10-volt source depending upon where we connect ground.

Another example is shown in Figure 2-23E. Here, two batteries are connected in series, with the ground connection between them. Thus, the zero reference is at point B. Since the top battery has an emf of 10 volts, the voltage at point C, with respect to ground, is +10 volts. The lower battery has an emf of 6 volts. Because the positive terminal is connected to ground, the emf at point A, with respect to ground, is –6 volts.

We sometimes loosely speak of the voltage at a particular point. Actually, voltage is always the measure of the potential difference between two points. Thus, in Figure 2-23E, when we speak of the voltage at point A, what we really mean is the voltage between point A and ground.

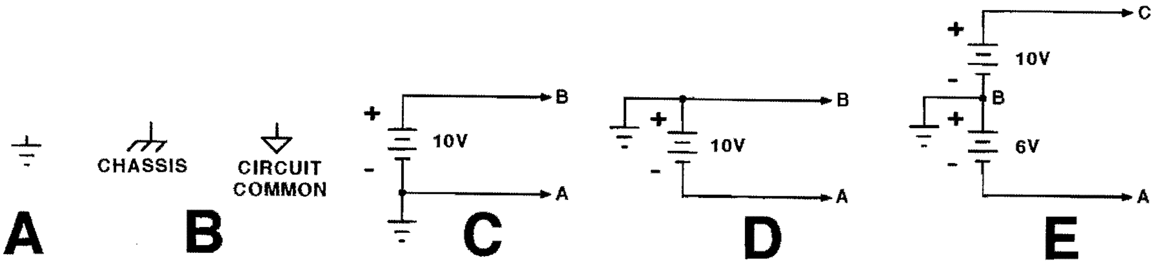


Figure 2-23

The polarity of the voltage depends upon the connection to ground.

Programmed Review

57. Voltages are normally measured with respect to one common point. This common point acts as a zero reference and is called ____________ .

58. (ground) Heavy electrical machines are often grounded by connecting them to a rod which is driven deep into the earth. Electric clothes dryers are often grounded by connecting them with a heavy wire to a cold water pipe. This type of ground is sometimes called earth ____________ .

59. (ground) Most small electronic devices are not connected to earth ground. Nevertheless, these devices have a common point that serves as the reference against which all voltages are measured. This reference point is also called ____________ .

60. (ground) This point may or may not be at the same potential as earth ground. Generally, this point simply "floats" and is not connected to earth ground in any way. Thus, this type of ground is simply a common point which serves as a zero ____________ .

61. (reference) The concept of ground is very important to the concept of negative and positive voltages. For example, a 12-volt battery becomes a +12 volt source when the ____________ terminal is connected to ground.

62. (negative) On the other hand, the same battery becomes a –12 volt source when the ____________ terminal is connected to ground.

63. (positive) In a circuit which contains ground, we take it for granted that the voltages are measured with respect to ground. Thus, when we say that the voltage at point A is +12 volts, what we mean is that +12 volts of emf exists between point A and ____________ .

64. (ground)

MEASURING VOLTAGE

The device used for measuring voltage is called the voltmeter. There are many different types of voltmeters in use today. Many use a mechanical (analog) meter movement like the one shown in Figure 2-24A. Here, you read the voltage on a scale behind the moving pointer. Another type, called the digital voltmeter, is much more popular today. It is shown in Figure 2-24B. Here, the voltage is displayed as numerals. This type of meter is more accurate and is easier to read. Generally, it is also more expensive.

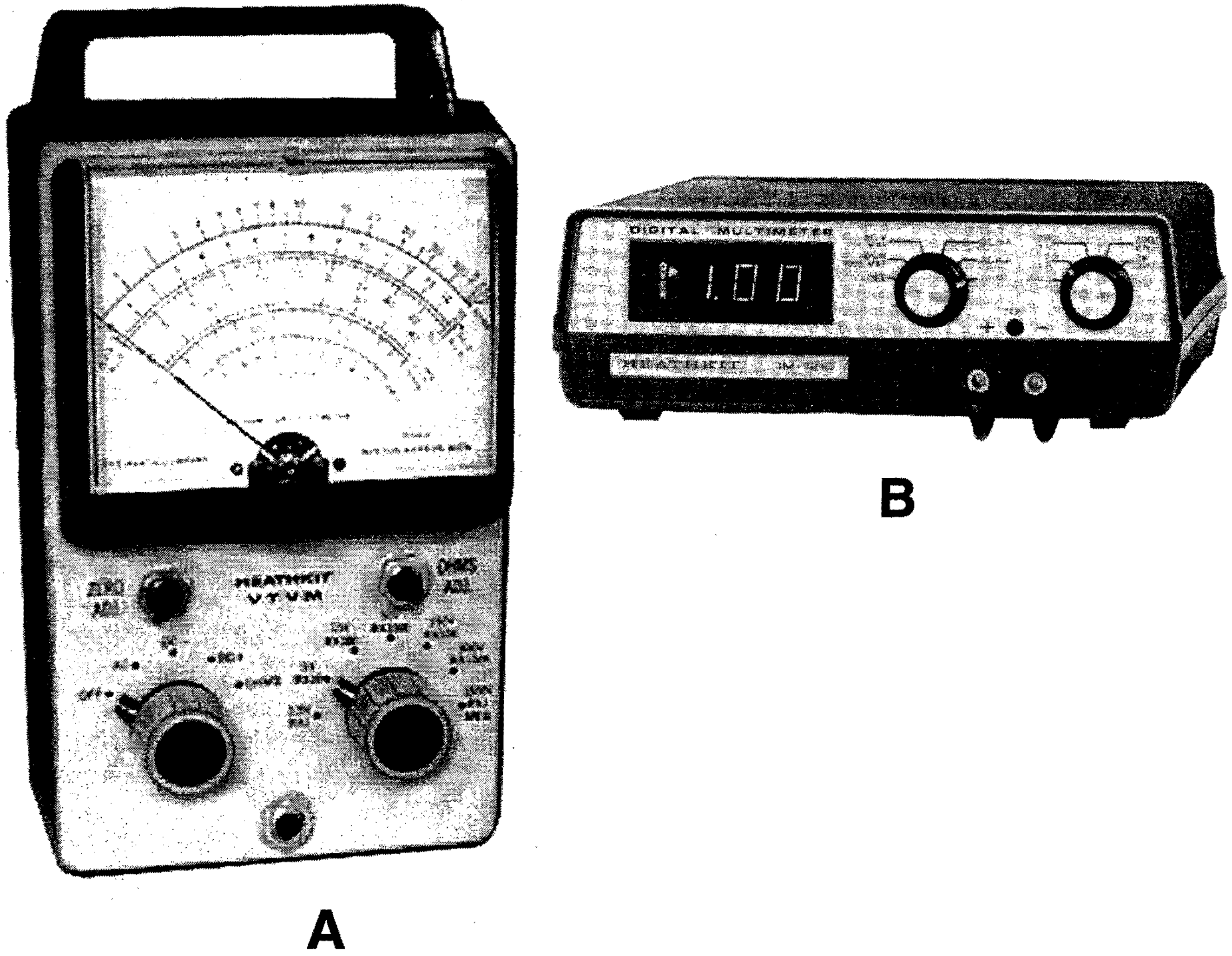


Figure 2-24
Two types of voltmeters.

Regardless of the type of voltmeter, you must take certain precautions to ensure accurate readings. To begin with, voltage is always measured between two points. The schematic symbol for the voltmeter is shown in Figure 2-25A. Notice that one of the leads is marked negative while the other is marked positive. As with the ammeter discussed earlier, you should observe polarity when you use a voltmeter. This means that the negative lead must go to the more negative of the two points across which the voltage is to be measured. Modern digital voltmeters have automatic polarity sensing and can be connected either way in a circuit, but it is a good idea to get into the practice of observing the correct polarity anyway.

Fortunately, the voltmeter is much easier to use than the ammeter. With the voltmeter, the circuit under test does not need to be broken or disturbed in any way. To measure the voltage between two points, you merely touch the two leads of the voltmeter to the two points. However, you should observe polarity. Figure 2-25B shows how the voltmeter is connected to measure the voltage drop across the lower lamp. Notice that the negative lead is connected to the more negative point. Notice also that the meter is connected directly across the lower bulb.

In this case, the meter is measuring a voltage drop. If the switch is opened so that current flow stops, the voltage drop disappears and the meter reading falls to zero.

Figure 2-25C shows a different circuit with the meter connected to measure the voltage rise of the lower battery. Once again polarity is observed and the meter is connected directly across the component. Here, the meter is measuring a voltage rise, rather than a voltage drop. Therefore, the voltage remains constant when the switch is opened. Notice that the voltage rise does not depend upon current flow.

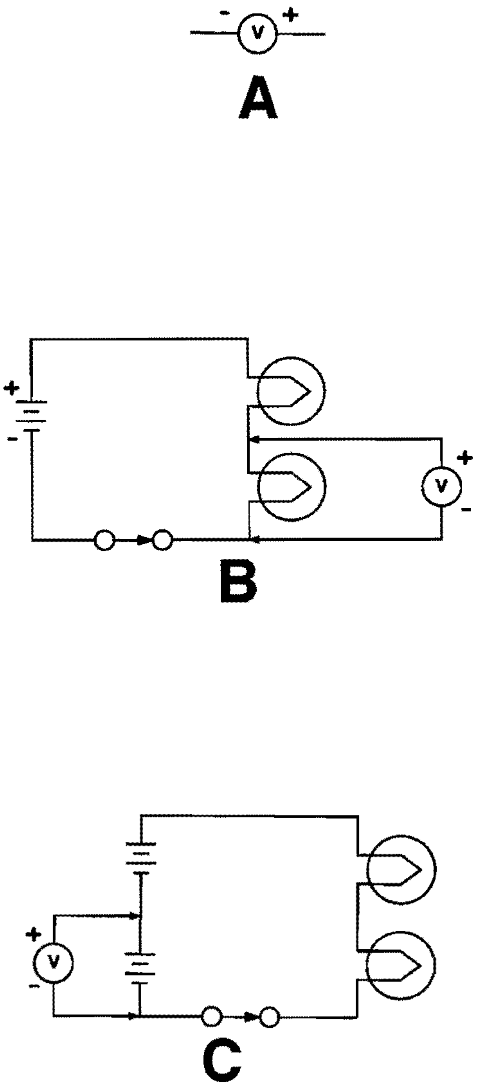


Figure 2-25
How to connect a voltmeter.

You should take a couple of precautions when you use a voltmeter. First, you should always make certain that the voltage you are going to measure is not higher than the meter can measure. If it is, the high voltage may damage the meter. Also, you should be certain the meter is on the proper range. For example, you should not attempt to measure 100 volts with the meter set to the 1 volt range. This, too, may damage the meter. When you are unsure of the value of voltage being measured, make your first measurement with the meter on a high range. This will help prevent the unknown voltage from pegging (in the case of an analog meter) or damaging the meter.

For your own safety, there are some other precautions that you should observe. You should hold the meter leads only by the insulated portions. Otherwise, you may receive an electrical shock. As you have seen, in most electronic devices, voltages are measured with respect to ground. Therefore, when you work on electronic equipment, it is a good idea to connect one lead to ground and leave it there. This way only one hand is required to make voltage measurements. You can hold the other hand away from the equipment. This greatly reduces your chances of receiving an electrical shock, since there is no complete path for current to flow through your body.

Programmed Review

65. Voltage is measured between two points that have a difference of potential. The device used for measuring voltage is the ____________ .

66. (voltmeter) Whereas, the ammeter was connected in series with the circuit, the voltmeter is connected across a part of a circuit. If the voltmeter is connected across a voltage source, the emf measured represents a voltage ____________ .

67. (rise) However, when the meter is connected across a load which consumes energy, the emf measured represents a voltage ____________.

68. (drop) The voltmeter cannot tell the difference between a voltage drop and a voltage rise. It simply measures the potential difference without regard to the nature of the emf.

When the voltmeter is used, the negative lead should connect to the more negative point while the positive lead goes to the more positive point. This is called observing ____________ .

69. (polarity) You should take certain precautions when you use a voltmeter. Four examples are:

1. Use only one hand whenever possible.
2. Touch only the insulated portions of the leads.
3. Observe polarity.
4. Be certain that the voltage does not exceed the capabilities of the meter.

The first two precautions are designed to protect the user. The next two are designed primarily to prevent damage to the ____________ .

70. (voltmeter)

EXPERIMENT 2

Measuring Voltage

OBJECTIVES: *To gain practice measuring voltage.*

To familiarize you with the operation and capabilities of your Trainer and meter.

To determine how the two power supply sections on your Trainer are connected.

Introduction

The voltages used in these experiments are provided by the ±DC power supply on the Heathkit Analog Trainer. Figure 2-26 shows the front panel area of typical power supply sections. A variable positive voltage is provided between the POS terminal and the GND terminal. The value of this voltage can be adjusted by the + voltage control knob.

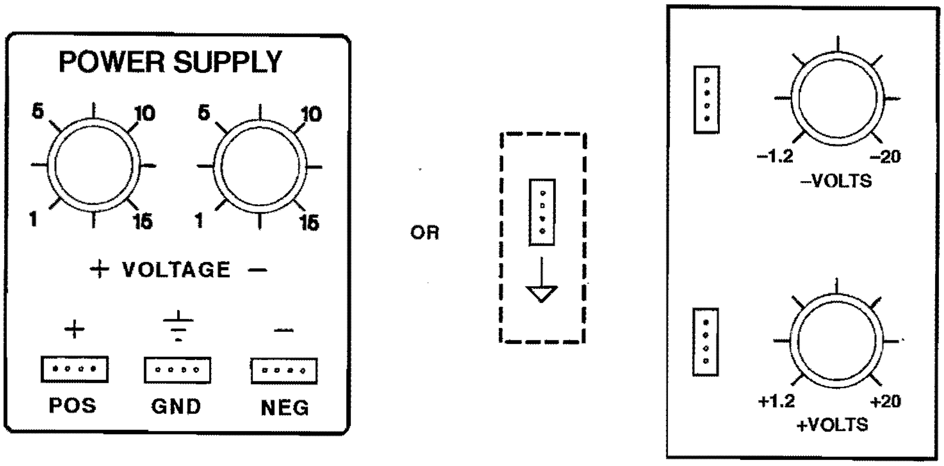


Figure 2-26
Typical power supply sections on the Trainer.

A variable negative voltage is provided between the NEG terminal and the GND terminal. This voltage can be adjusted by the – voltage control knob. Notice that the GND (ground) terminal is common to both supplies. Generally, voltages are measured with respect to this point.

Before you begin this experiment, read the instructions provided with your meter. Voltmeters vary greatly in their ranges, scales, and capabilities. However, if you know how to use your meter, you will have no problem completing the experiments in this course.

Material Required

1 — Heathkit Analog Trainer
1 — Voltmeter (multimeter) with test leads

Procedure

1. Plug in the Trainer and switch it ON. Turn both voltage controls fully counterclockwise (ccw).

2. Set up your voltmeter to measure DC voltages of at least 10 volts. NOTE: If your meter does not have a DC range setting exactly equal to this voltage (10V), you should use the closest setting **above** it. For example, if your meter has settings of .25, 2.5, 10, 50, and 250 volts, and a 15V (minimum) range setting is indicated, set your meter to the 50V setting.

3. Attach the positive lead of your voltmeter to the + voltage terminal on the Trainer. Depending upon the type of leads on your meter, you may find it necessary to insert a short length of hook-up wire into the POS voltage terminal to make contact for measuring voltage. Similarly, attach the negative (common) lead of your voltmeter to the GND terminal on your Trainer.

4. With the + voltage control fully ccw, measure the voltage output. Set your meter to the lowest DC voltage range that will allow you to measure the voltage without driving your meter past full-scale deflection. The voltmeter indicates ______________ volts.

5. Switch your meter to the proper range for measuring voltages of at least 5 volts. Set the + voltage control on the Trainer to approximately 1/3 cw (approximately 5V). The voltmeter indicates __________ volts.

6. Switch your meter to the proper range for measuring voltages of at least 15V. Set the + voltage control to approximately 2/3 cw (approximately 10V). The voltmeter indicates __________ volts.

7. Switch your meter to the proper range for measuring voltages of at least 50V. Set the + voltage control to fully cw. This is the maximum voltage that the positive power supply can produce. The voltmeter indicates __________ volts.

8. Return the + voltage control to its full ccw position. Make sure that the – control is also in its full ccw (minimum) position. Remove the positive probe of the voltmeter from the POS terminal on the Trainer. As you carefully watch the display on your meter for a slight negative deflection (or symbol on a digital meter) attach the positive (red) probe of your meter to the NEG terminal on the Trainer. The meter indicates __________ (+ or forward/– or reverse).

NOTE: If you have a digital meter, skip step 9 and go to step 10. If you have an analog (meter movement) type meter perform the next step (9).

9. Leave your negative meter lead connected to the Trainer ground and set your meter select switch to –DC. If you do not have a –DC mode on your meter, interchange your meter test leads (connect the positive meter lead to the Trainer's GND terminal and the negative test lead to the – NEG voltage terminal of the Trainer).

10. Measure the voltage between the NEG and GND terminals with the – voltage control set to the positions indicated in the following table. Record the voltages indicated in the spaces provided. When you finish, switch the Trainer OFF.

–NEG Voltage Control Setting	Voltage Measured
full counterclockwise	__________ V
1/3 clockwise	__________ V
2/3 clockwise	__________ V
full clockwise	__________ V

Discussion

In this experiment you gained some practice using your Trainer and voltmeter. First, you measured the voltages produced by the positive power supply. You saw that this voltage can be adjusted by the + voltage control to any value from about +1 volt to over +15 volts. In step 8 you saw that the maximum voltage provided by this supply is in the 15- to 20-volt range.

Next, you measured the voltage produced by the negative power supply. This voltage can be set to any value from about –1 volt to over –15 volts.

In step 8, the meter should have deflected in the negative direction when you attempted to measure the voltage. The reason for this backwards reading was that you did not observe polarity. As you saw, this problem is easily corrected by simply interchanging the meter leads. Some meters have a polarity-reversing switch. This switch automatically interchanges the leads in the meter so you don't have to do so externally. Digital meters are even more convenient to use because they generally display a + or – symbol to indicate polarity without your needed to interchange or switch the test leads.

If you think of the power supplies on the Trainer as batteries, they are connected as shown in Figure 2-27. You will recognize this as a series-aiding connection. Notice that any voltage produced here, whether positive or negative, is referenced to the ground potential, which is at zero volts. The +POS terminal provides voltages above ground, while the –NEG terminal provided voltages below ground.

Incidentally, we will be using the symbols shown in this figure for the power supplies on the Trainer. Although these are not "standard" symbols, we will use them to simplify our schematic diagrams. The battery symbol indicates that the power supply produces DC voltages similar to a battery. In fact, when you see the schematic symbol for a battery, you can generally assume that either a battery, or a good DC power supply (such as those on your Trainer) may be used. The arrow (through the battery symbol) indicates that the DC voltage is adjustable.

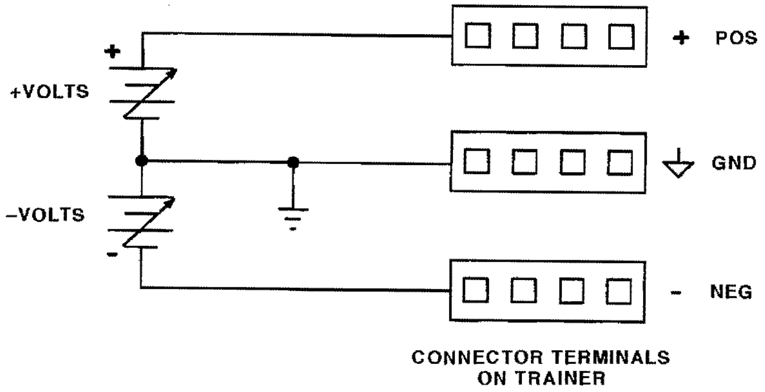


Figure 2-27

Internal Trainer power supply connections.

EXPERIMENT 3

Voltage Rises and Voltage Drops

OBJECTIVES: *To see how a voltage rise differs from a voltage drop.*

To verify that the sum of the voltage drops is equal to the sum of the voltage rises.

Material Required

1 — Heathkit Analog Trainer
1 — Voltmeter (multimeter) with test leads
1 — 2000 Ω, 5%, 1/2-watt resistor (red-black-red-gold)
2 — 1000 Ω, 5%, 1/2-watt resistor (brown-black-red-gold)
1 — Slide switch (#60-2)
1 — Roll #22 insulated copper wire
1 — 25 watt (min.) solder iron/solder
1 — Diagonal wire cutter/stripper

Procedure

1. If necessary, cut two 3" lengths from the roll of #22 insulated copper (hookup) wire. Remove about 1/4" of insulation from each end. Solder one end of each wire to the two terminals of the slide switch as shown in Figure 2-28.

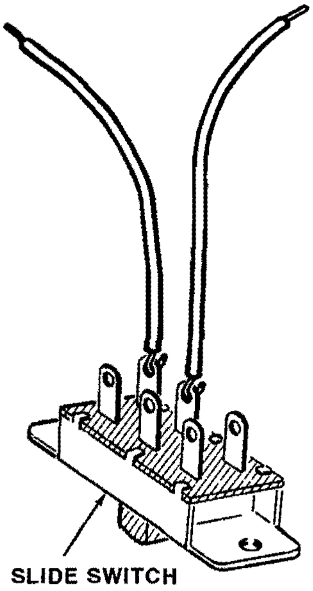


Figure 2-28
Solder leads to the switch.

2. Use the three resistors and the slide switch to construct the circuit shown in Figure 2-29. Draw the schematic diagram for this circuit.

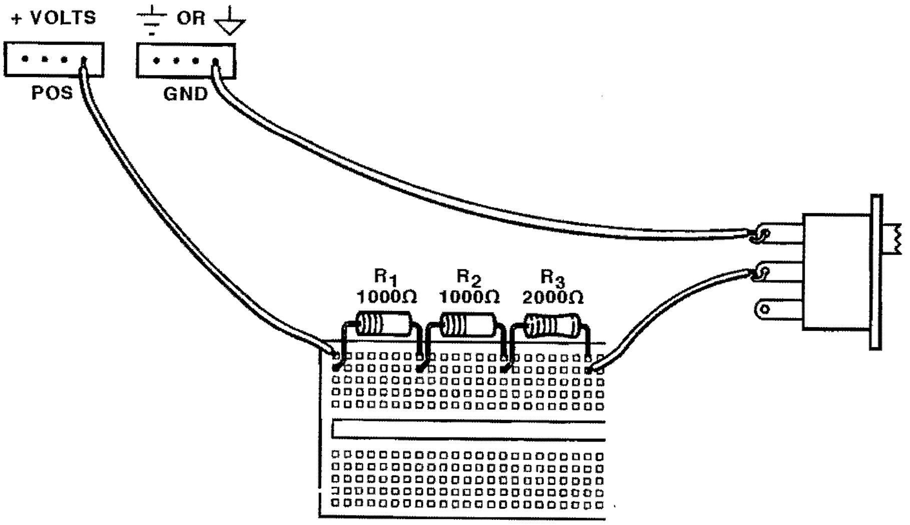


Figure 2-29
Circuit for Experiment 3.

3. Connect your voltmeter between the POS and GND terminals of the power supply. Then adjust the + voltage control until the meter reads exactly 10 volts. Operate the slide switch. Does this voltage disappear when current stops flowing? __________. Is this a voltage rise or a voltage drop? __________.

4. Observe polarity and connect the voltmeter across the resistor labeled R_3. Measure the voltage. If the voltage at this point is 0, operate the slide switch so that current flows through the circuit. The voltage across R_3 is __________ volts. Note that when the switch is closed, the slide is at the end where the two wires are soldered to the switch terminal.

5. Operate the slide switch several times and verify that the voltage across R_3 (or any other resistor) disappears each time the switch is opened. Is this a voltage drop or a voltage rise? __________.

6. The schematic for the circuit that you have constructed in step 2 is shown in Figure 2-30A on the next page. Rebuild this circuit so that it appears like the circuit shown in Figure 2-30B.* Notice that this only requires you to rearrange the resistors. Measure the voltage drop across R_2. The voltage drop is __________ volts.

---

* As mentioned earlier, always turn your Trainer's power off when you connect or modify circuits.

7. Now reconfigure the circuit so that it appears like the one shown in Figure 2-30C and measure the voltage across R_1. The voltage drop across R_1 is ____________ volts.

8. Add the three voltage drops together. The total of the voltage drops is ____________ volts. Is this the same as the voltage rise which you setup in Step 3? ____________

9. Switch the Trainer OFF. If possible, save your parts and equipment for the next experiment.

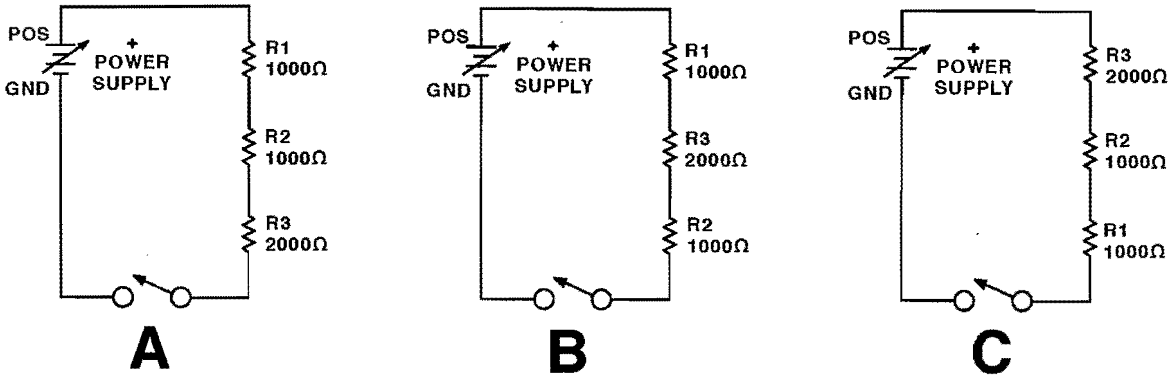

POS
GND
+
POWER SUPPLY
R1 1000Ω
R2 1000Ω
R3 2000Ω
A
POS
GND
+
POWER SUPPLY
R1 1000Ω
R3 2000Ω
R2 1000Ω
B
POS
GND
+
POWER SUPPLY
R3 2000Ω
R2 1000Ω
R1 1000Ω
C

Figure 2-30

Schematic diagram of the circuit shown in Figure 2-29.

Discussion

The +10 volts that you applied to the circuit represents a voltage rise equal to ten volts. You proved that this is a voltage rise because it exists whether or not the switch is closed or current is flowing through the circuit.

In step 4 you measured the voltage drop across R_3. You should have found this to be approximately 5 volts. Next, in step 5, you proved that the voltage drop across the resistor existed only after the switch was closed allowing current to flow. After rearranging the resistors, to get R_1 and R_2 into the last (grounded) position for measurement, you should have found the remaining 5 volts dropped as 2.5 volts across R_1, and 2.5 volts across R_2.

You saw how the 10 volts was dropped (in three steps) between the +POS and GND terminals of the Trainer power supply when the switch was closed, which allowed current to flow through the three series resistors. Because the resistors are in series, the sum of each individual drop must add up to the total voltage applied, in this case, 10 volts. In general, to observe the individual voltage drops across each resistor, you could simply measure across each one without rearranging them (so that each was referenced to ground before measuring as you did). This is not true in all cases, however. The reason is equipment grounding.

Many DC power supplies (including those on most Trainers) have their ground terminals connected to earth ground (the center prong on the line plug). Unfortunately, some bench-type meters also have their common test leads internally connected to earth ground (through a grounded line cord). While in most cases it is okay to measure series voltage drops by simply connecting your voltmeter across any series resistor (regardless of its placement with respect to ground in the circuit), you can see that if you have a meter with an earth grounded common test lead, problems arise. The common (earth grounded) meter test lead introduces an unwanted ground into the circuit being measured, and an unexpected result can occur. Consider the case of the test circuit in Figure 2-30A. If you tried to measure its voltage drop with an earth grounded common lead meter you would see the entire 10 volts dropped across R1! This is obviously misleading because each series resistor has to drop some fraction (less than 100%) of the voltage applied.

Fortunately, the chances are that you do not have this type of meter (you definitely don't if you're using a battery-operated meter). However, even if you do, you should have obtained good results with this experiment because each resistor was rearranged to have one side connected to the Trainer ground before you measured its individual voltage drop. This is the same voltage drop that the resistor has in the circuit no matter where it is placed. If your meter does not have an earth grounded common test lead, you can verify this by simply measuring across each resistor as connected in Figure 2-30A.

Finally, although not discussed in this unit, you may have noticed that the voltage dropped across the 2000 ohm resistor was twice the voltage dropped across the 1000 ohm resistor. The relationship between the amount of resistance and the amount of the voltage drop will be discussed in detail in Unit 4.

The +10 volts that you applied to the circuit represents a voltage rise. As you saw, this voltage rise is dropped between the +POS and GND terminals (of the Trainer Power Supply) by three resistors. Because the resistors are in series, the sum of each individual drop must add up to the total voltage applied, that is +10 volts.

EXPERIMENT 4

Shorts and Opens

OBJECTIVE: *To determine the voltage characteristics of a short and an open.*

Introduction

In electrical work, a short is a path from one point to another which offers very little opposition to current flow. A length of conductor can be considered a short. A closed switch is also a short. A short is characterized by a very small voltage drop, a current which is largely determined by the ability of other circuit components to resist current flow. Ideally, the short itself provides no opposition to current flow and therefore, produces no voltage drop.

An open has exactly the opposite characteristics. It offers a very high or, "infinite," opposition to current flow. Consequently, no current can flow through an open circuit. The voltage across an open is equal to the applied voltage in the circuit. These points can be easily verified by experimentation.

Material Required

Same as Experiment 3 (no soldering iron).

Procedure

1. Reconstruct the circuit shown in Figure 2-30A. Switch the Trainer ON. Test the applied voltage to insure that it is 10 volts. Be sure to observe polarity when you test this voltage.

2. Observe polarity and connect the voltmeter across the switch.

3. Set the switch to its closed (ON) position. The voltage across the switch is _________ volts.

4. Next, set the switch to its open (OFF) position. The voltage across the switch is now ___________ volts.

5. Disconnect the meter from across the switch. Then observe polarity and connect it across R_3. Close the switch. The voltage measured across R_3 is __________ volts.

6. Cut a short piece of hookup wire and remove 1/4 inch of insulation from each end. Connect this wire across R_1 (in parallel) to short R_1. Does the voltage across R_3 increase or decrease? ____________. The voltage across R_3 is ____________ volts.

   How do you account for the voltage change across R_3? ____________

   ____

   ____

7. Switch the Trainer OFF.

Discussion

In this experiment you demonstrated some of the characteristics of opens and shorts. In Step 3 you measured the voltage across the closed switch. When the switch is closed it acts as a short across the meter. Since the short offers virtually no opposition to current flow, all the current flows through the switch while none flows through the meter. Consequently, the meter indicates 0. The voltage drop across a short circuit is always 0 volts.

Next, in Step 4 you opened the switch. With no current flowing in the circuit, the voltage measured across the switch is equal to the applied voltage. In this case, the voltage is 10 volts. The reason for this will become clear when you study resistance in a later unit.

In Steps 5 and 6 you demonstrated what happens in a series circuit when one resistor is shorted out. You first measured the voltage across R_3 as shown in Figure 2-31A. You should have found the voltage to be about 5 volts.

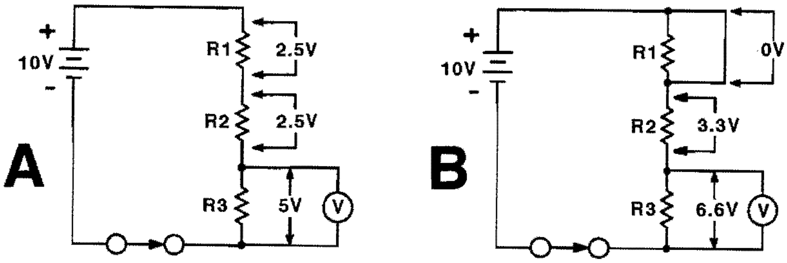


Figure 2-31
A short across a resistor changes the voltage distribution in the circuit.

Next you placed a short (wire) across R_1 as shown in Figure 2-31B. You saw that the voltage drop across a short is 0 volts. Thus, the applied voltage must now be dropped only by R_2 and R_3. R_3 drops approximately 6.6 V while R_2 drops about 3.3 V. Kirchoff's voltage law still applies, but the applied voltage is dropped across only two resistors.

SUMMARY

The following is a point-by-point summary of Unit 2. If you are in doubt about any of the facts listed here, you should review the appropriate portion of the text.

Electromotive force, or emf, is the force which moves electrons. This force is a natural result of Coulomb's law.

Potential difference is another name for the same force. It represents the potential for moving electrons.

Emf or potential difference exists between any two charges which are not exactly alike.

A difference of potential exists between any uncharged body and any charged body.

An emf exists between two unequal positive charges, between unequal negative charges, and between any negative charge and any positive charge.

Voltage is the measure of emf or potential difference.

The unit of voltage is the volt.

One volt is equal to one joule of energy or work per coulomb of transferred charge.

The joule is the metric unit of work, and is equal to 0.738 foot pounds.

The millivolt (mV) is 1/1000 volt. The microvolt (μV) is 1/1,000,000 volt. The kilovolt (kV) is 1000 volts. The megavolt (MV) is 1,000,000 volts.

Emf can be produced in several different ways. The most common method uses magnetism and mechanical motion. Other methods use chemical reactions, friction, light, pressure, or heat.

A cell is an electrochemical device which contains negative and positive electrodes that are separated by an electrolyte.

A battery is a combination of two or more cells.

There are two basic types of cells — the primary cell and the secondary cell.

The primary cell cannot be recharged.

The secondary cell can be recharged.

The dry cell uses a paste-like electrolyte and can be used in any position.

The wet cell uses a liquid electrolyte and can be operated only in the upright position.

The most common type of dry cell uses an electrolyte of ammonium chloride and zinc chloride. The positive electrode is carbon and the negative electrode is zinc. A new dry cell produces an emf of about 1.5V. It is a primary cell.

The most common type of wet cell is used in the lead-acid battery.

The electrolyte is sulfuric acid and water. The positive electrode is lead dioxide and the negative electrode is pure lead. It produces an emf of about 2.1V. A secondary cell can be recharged repeatedly.

The voltage produced by a cell is determined by the chemical reaction and not by the size of the cell. However, current capacity is determined by the size.

When two or more cells are connected series-aiding, the individual voltages add. Thus, you can form a 6-volt battery by connecting four 1.5 volt cells in the series-aiding arrangement.

When two cells are connected series-opposing, the voltage produced by one cell is subtracted from that produced by the other. You should normally avoid this connection.

When two or more cells are connected in parallel, the output voltage is the same as that for any one cell. That is, the voltages do not add. However, the current capacity does increase.

Cells can be connected in a series-parallel arrangement so that both the voltage and the current capacity increase.

A voltage can exist at two different points in a circuit: Where emf is produced and where energy is used.

A voltage which exists because emf is being produced is called a voltage rise.

A voltage which exists because energy is being used is called a voltage drop.

A voltage rise exists with or without current flow.

A voltage drop exists across a component only when current flows through the component.

If one joule of energy is consumed by a load when one coulomb of charge flows through it, then the voltage drop across the load is one volt.

In a circuit in which current is flowing, the sum of the voltage drops is equal to the sum of the voltage rises.

Ground is the name given to the point in a circuit that is used as the zero reference. Often this is the metal chassis or frame of the electronic device. All grounds are not necessarily "earth" grounds. They can be a common reference point within a circuit.

Voltages may be negative or positive with respect to ground. A battery can be connected as a negative voltage rise or as a positive voltage rise depending upon how it is connected to ground.

The device used to measure voltage is called the voltmeter.

Voltage is measured between two points that have a difference of potential.

You should observe polarity when you connect a voltmeter to a circuit. The voltmeter is connected across (or in parallel with) the voltage rise or voltage drop to be measured. Thus, you do not need to break the circuit under test when you measure voltage.

A short offers no opposition to current flow. If a short is placed across a component, all current will pass through the short and no current will pass through the component. The voltage drop across a short is zero.

An open offers "infinite" opposition to current flow. In a series circuit, the voltage measured across an open is equal to the voltage rise in the circuit.

UNIT EXAMINATION

1. Which of the following is **not** another name for the force which we call voltage?

   A. Electromotive force.
   B. Potential difference.
   C. EMF.
   D. Current.

2. A potential difference does **not** exist between:

   A. two identical positive charges.
   B. a positive charge and an equal negative charge.
   C. a charged body and an uncharged body.
   D. a body with a high positive charge and another body that has only a slight positive charge.

3. The unit of measure of the electromotive force is the:

   A. volt.
   B. joule.
   C. ampere.
   D. coulomb.

4. A device that converts chemical energy to electrical energy is called a:

   A. piezoelectric device.
   B. thermocouple.
   C. generator.
   D. cell.

5. A secondary cell is a:

   A. dry cell.
   B. solar cell.
   C. cell that can be recharged.
   D. battery that uses sulfuric acid and water as an electrolyte.

6. The lead-acid cell is a:

   A. wet cell that produces an emf of about 1.5 volts.
   B. wet cell that produces an emf of about 2.1 volts.
   C. dry cell that produces an emf of about 1.5 volts.
   D. dry cell that produces an emf of about 2.1 volts.

7. A 9-volt battery can be formed by connecting six 1.5-volt cells in a:

   A. series-aiding arrangement.
   B. series-opposing arrangement.
   C. series-parallel arrangement.
   D. parallel arrangement.

8. What is the minimum number of identical cells required to produce a battery that has a voltage twice that of an individual cell and a current rating three times that of an individual cell?

   A. 3.
   B. 6.
   C. 12.
   D. 9.

9. One difference between a voltage drop and a voltage rise is that the voltage drop:

   A. can exist with or without current flow in the circuit.
   B. exists only when current flows in the circuit.
   C. is only one-half the value of the voltage rise in the circuit.
   D. is twice the value of the voltage rise.

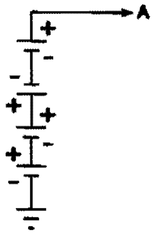


Figure 2-32
Circuit for Question 10.

10. Four cells are connected as shown in Figure 2-32. What is the voltage at point A with respect to ground?

   A. + 6.0V.
   B. + 4.5V.
   C. + 3.0 V.
   D. – 4.5 V.

11. Look at the circuit shown in Figure 2-33. If R_1 is replaced with a length of wire, what happens to the voltage drop across R_2?

   A. The voltage drop increases.
   B. The voltage drop decreases.
   C. The voltage drop remains the same.

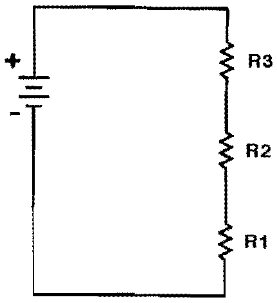


Figure 2-33
Circuit for Question 11.

12. Look at the circuit shown in Figure 2-34. If R_1 and R_2 are identical resistors, what is the voltage drop across R_1?

A. 6 volts.
B. 0 volts.
C. 3 volts.
D. 2 volts.

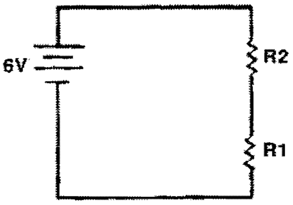


Figure 2-34
Circuit for Question 12.

13. Which of the circuits shown in Figure 2-35 shows the proper method of connecting a voltmeter to measure the voltage drop of R_1?

A. Figure 2-35A.
B. Figure 2-35B.
C. Figure 2-35C.
D. Figure 2-35D.

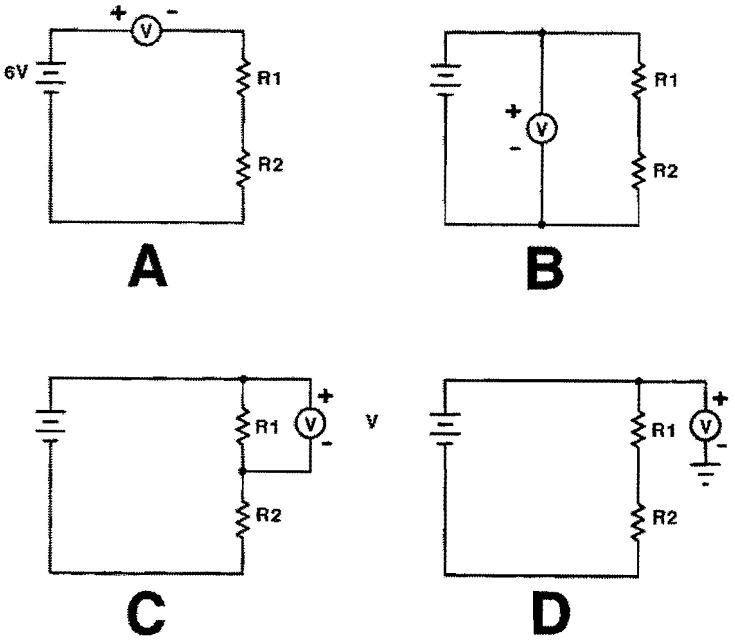


Figure 2-35
Circuits for Question 13.

14. Look at the circuit shown in Figure 2-36. What voltage does the voltmeter read when S_1 is open and when S_1 is closed?

A. 6 volts when S_1 is open; 0 volts when S_1 is closed.
B. 0 volts when S_1 is open; 6 volts when S_1 is closed.
C. 6 volts when S_1 is open; 6 volts when S_1 is closed.
D. 0 volts when S_1 is open; 0 volts when S_1 is closed.

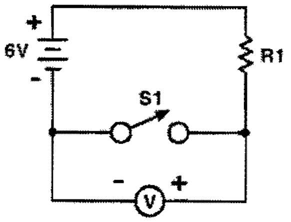


Figure 2-36
Circuit for Question 14.

15. The voltmeter is generally easier to use than the ammeter because:

    A. you do not need to observe polarity when you use the voltmeter.
    B. you do not need to break the circuit under test to measure the voltage.
    C. you do not need to observe safety precautions when you use the voltmeter.
    D. voltage drops can be measured without applying power to the circuit under test.

16. The current capacity of a cell is determined by the:

    A. chemical reaction in the cell.
    B. size of the cell.
    C. number of electrodes in the cell.
    D. amount of electrolyte used in the cell.

17. The voltage output of a cell depends upon the:

    A. chemical reaction in the cell.
    B. voltage at which the cell is recharged.
    C. size of the cell.
    D. the application in which the cell is used.

18. The three main parts of any cell are the:

    A. electrodes and the case.
    B. electrolyte and the case.
    C. electrodes and the electrolyte that separates them.
    D. positive ions and the electrolyte.

19. In electrical terminology, a path from one point to another that offers no opposition to current flow is called a/an:

    A. open.
    B. voltage rise.
    C. short.
    D. ground.

20. A/an ____________ offers infinite opposition to current flow.

    A. short
    B. ground
    C. open
    D. potential difference

EXAMINATION ANSWERS

1. D — Electromotive force, potential difference, and emf are other names for the force which we loosely call voltage. Current is not a correct name for this force.

2. A — A potential difference does not exist between identical charges. However, it does exist between any two charges which are not identical in both polarity and magnitude.

3. A — The unit of electromotive force or voltage is the volt. Joule is the unit of energy; ampere is the unit of current; and coulomb is the unit of charge.

4. D — The cell or battery converts chemical energy to electrical energy.

5. C — By definition a secondary cell is one which can be recharged.

6. B — The lead-acid cell is a wet cell that produces an emf of about 2.1 volts.

7. A — The six 1.5 volt cells must be connected in the series-aiding arrangement if their voltages are to add.

8. B — To double the voltage, two cells must be connected in the series-aiding arrangement. However, to triple the current capacity, three of these arrangements must be connected in parallel. Therefore, a total of six cells is required.

9. B — A voltage drop exists only when current flows in the circuit.

10. C — Notice that three of the batteries are connected series-aiding. However, one is connected series-opposing. The opposing battery cancels the voltage produced by one of the aiding batteries. Consequently, the output voltage is +3.0 volts.

11. A — The voltage drop across R_2 increases. When R_1 is shorted, the applied voltage must be dropped by only two resistors instead of three. Thus, the voltage dropped by each of the remaining resistors increases.

12. C — If the two resistors are identical, each must drop half of the applied voltage or 3 volts.

13. C — This is the only circuit which shows the meter connected directly across R_1.

14. A — When S_1 is open, the voltage measured by the meter is equal to the voltage rise in the circuit, or 6 volts. However, when S_1 is closed, the meter is shorted, so it reads 0 volts.

15. B — Since the voltmeter is placed across the circuit rather than in series with it, the circuit does not need to be broken.

16. B — The size of the cell determines the current capacity of the cell. The larger the cell is, the greater the current it can supply to a circuit.

17. A — The voltage produced by a cell depends upon the chemical reaction within the cell. For instance, regardless of its size, a lead-acid battery will produce 2.1 volts of emf. However, as stated in answer 16, a larger cell will deliver more current.

18. C — The three main parts of a cell are the two electrodes and the electrolyte that separates them.

19. C — A short offers no opposition to current flow.

20. C — An open is a break in the current path through a circuit. Current cannot flow through this break; therefore, it offers infinite resistance to current flow.

UNIT 3

RESISTANCE

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INTRODUCTION

In this unit, you will study resistance. Resistance is a property which opposes current flow. All materials have this property to some extent. Some materials such as glass and rubber offer a great deal of opposition to current flow. They allow almost no current to flow through them. Thus, they have a very high resistance. Other materials such as silver and copper offer very little opposition to current flow. Therefore, they have a very low resistance.

This unit deals with the characteristics of resistance. It describes what resistance is, how it is measured, and how it is used.

UNIT OBJECTIVES

When you complete this unit, you will be able to:

1. Define the following terms: Resistivity, resistance, conductance, ohm, thermistor, potentiometer, LDR, positive temperature coefficient, negative temperature coefficient, specific resistance, and rheostat.
2. Name four factors that determine the resistance of a substance and state the relationship that these factors have to the resistance of a substance.
3. State the difference between a conductor and an insulator, in terms of resistance.
4. Given the gauge and type of wire, calculate the resistance of a length of wire.
5. Determine a resistor's value and tolerance by examining its color code.
6. Determine a resistor's power rating by examining its size.
7. Calculate the total resistance of resistors in series, parallel, and series-parallel configurations.
8. State the effects of connecting resistors in series and parallel, in terms of circuit resistance.
9. Describe the correct method for using an ohmmeter.
10. State the relationship between resistance, current, and voltage.
11. Name three types of fixed resistors.

UNIT ACTIVITY GUIDE

	Completion Time
☐ Read "Basic Concepts."	______
☐ Complete Programmed Review Frames 1 through 12.	______
☐ Read "Resistors."	______
☐ Complete Programmed Review Frames 13 through 24.	______
☐ Read "Connecting Resistors."	______
☐ Complete Programmed Review Frames 25 through 32.	______
☐ Perform Experiment 5.	______
☐ Perform Experiment 6.	______
☐ Perform Experiment 7.	______
☐ Perform Experiment 8.	______
☐ Study Summary.	______
☐ Complete Unit Examination.	______
☐ Check Examination Answers.	______

BASIC CONCEPTS

If a short length of *copper* is connected across a battery, a great deal of current will flow—so much, in fact, that the battery will quickly discharge. If the same length of *rubber* is connected across the same battery, no measurable current will flow. Obviously, copper and rubber have very different characteristics when it comes to passing current flow.

The difference stems from the atomic structure of the two materials. In copper, there are a great number of free electrons drifting aimlessly through the spaces between the atoms. When an emf is applied, a great number of electrons are free to move. Thus, a high current flow results. In rubber, the situation is different. Here, very few electrons drift around free between the molecules. Therefore, an emf can cause very few electrons to move. This results in little or no current flow.

Copper offers little opposition to current flow while rubber offers a great deal of opposition. This opposition to current flow is called resistance. Copper has very low resistance while rubber has very high resistance. The resistance of a material is determined largely by the number of free electrons in the material.

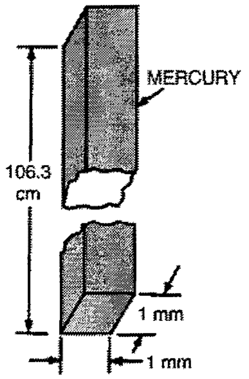
The Ohm

The unit of resistance is the *ohm*. This unit is named for Georg Simon Ohm, a German physicist who discovered the relationship between voltage, current, and resistance.

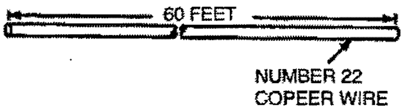
An ohm may be defined in several different ways. Originally, the ohm was defined as the resistance of a column of mercury which is 106.3 centimeters long and 1 square millimeter in cross sectional area. Once the ohm was defined in this way, it allowed anyone with the proper equipment to construct a 1 ohm standard. Unfortunately, this amount of resistance is hard to visualize.

It is helpful to think in terms of something with which we are more familiar. For example, the insulated wire provided with this course is number 22 copper wire. A length of this wire that is 60 feet long has a resistance of about one ohm.

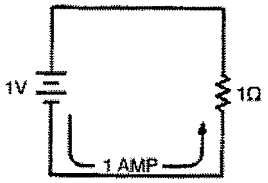
The most common way to define the ohm is in terms of voltage and current. One ohm is the amount of resistance which allows one ampere of current to flow in a circuit to which one volt of emf is applied. Or stated another way, if one volt causes one ampere of current in a circuit, the resistance of the circuit is one ohm. Figure 3-1 illustrates these three ways of defining the ohm.



RESISTANCE OF COLUMN OF MURCURY WITH DIMENSIONS SHOWN



RESISTANCE OF 60 FEET OF NUMBER 22 COPPER WIRE



RESISTANCE WHICH ALLOWS ONE AMPERE TO FLOW WHEN EMF IS 1 VOLT

Figure 3-1
The ohm.

The Greek letter omega (Ω) is commonly used to represent ohms. Thus, 1 ohm may be written 1 Ω. Also, one thousand ohms may be written as 1000 Ω, 1 kilohms, or as 1 kΩ (sometimes you may see an upper case K for kilo). Finally, one million ohms may be written as 1,000,000 Ω, 1 megohm, or as 1 MΩ. In electronics, the letter R is used to represent resistance. Thus, in the shorthand of electronics the statement "the resistance is ten ohms" may be written as an equation: "R = 10 Ω".

Resistivity

You cannot directly compare the resistance of two substances because the resistance depends upon the shape and size of the substance as well as the temperature. However, every substance has a property called *specific resistance* or *resistivity* which can be compared directly. The resistivity of a substance is defined as the resistance of a one-foot length of wire of the substance. Furthermore, the wire must be exactly 0.001 inch (1 mil) in diameter and the temperature must be exactly 20° centigrade. These requirements standardize the shape, size, and temperature of the substance so that only the atomic structure determines the resistance.

The resistivity of several substances is shown in Figure 3-2. Notice that silver has the lowest resistivity, while copper is a close second. Near the bottom of the list are glass and rubber. Silver and copper are the best conductors, while glass and rubber are two of the best insulators.

SUBSTANCES	RESISTIVITY IN OHM PER MIL. FOOT AT 20° C
SILVER	9.9
COPPER	10.4
GOLD	15.3
ALUMINUM	17.0
NICHROME	680.0
GLASS	10^{16}
RUBBER	10^{20}

Figure 3-2
Resistivity of common materials.

As you have seen, both conductors and insulators are important in electronics. Conductors have many free electrons and can conduct current very easily. Thus, they are used to carry electricity from one place to another. Most metals are good conductors. Thus, metals such as silver, copper, gold, aluminum, tungsten, zinc, brass, platinum, iron, nickel, tin, steel, and lead are all good conductors.

Insulators or nonconductors are substances which have few free electrons. They have very high values of resistivity. These substances are used to prevent an electrical connection. Most wires are coated with an insulator so that they do not accidentally short out when they are used to carry electricity. Some example of insulators are glass, rubber, plastic, mica, and dry air.

To summarize, it is the resistivity of a material which determines if the material is a conductor or an insulator. Resistivity is the resistance of a specific size and shape of the material at a specific temperature.

Conductance

Sometimes it is more convenient to think in terms of how well a material conducts current rather than to think in terms of how well it opposes current. Because of this, a property called *conductance* is often used. Conductance is just the opposite of resistance. It is defined as the ease with which a substance passes current flow. Mathematically, conductance is the reciprocal of resistance. This simply means that conductance is equal to the number 1 divided by the resistance. Or stated as an equation:

$$\text{Conductance} = \frac{1}{\text{Resistance}}$$

The letter G is used to represent conductance. Therefore, the equation is:

$$G = \frac{1}{R}$$

The unit of conductance is the *mho,* pronounced "moe." Notice that this is ohm spelled backwards. The mho is the reciprocal of the ohm. Therefore,

$$\text{mhos} = \frac{1}{\text{ohms}}$$

A resistance of 1 ohm equals a conductance of 1 mho. However, a resistance of 2 ohms equals a conductance of 1/2 or 0.5 mhos. Also, if the resistance is 1000 ohms, or 1 kilohm, the conductance is 0.001 mhos or 1 millimho. The term "siemens" is also used as a unit of conductance. It has the same meaning as the mho. That is, 1 mho equal 1 siemens.

In most cases it is more convenient to think in terms of ohms (resistance) rather than in terms of mhos (conductance). Therefore, you will be primarily concerned with resistance in this course. However, it is important to remember the mho, because a key characteristic of the vacuum tube and the field-effect transistor is given in mhos.

Factors That Determine Resistance

The single most important factor in determining resistance is the resistivity of the material. However, three other factors are also important. These are the length, the cross-sectional area, and the temperature of the material. This is the reason that these three variables had to be carefully defined in order to determine resistivity. Let's discuss each of these in more detail.

Length. The insulated wire with this course is number 22 copper wire. A 60-foot length of this wire has a resistance of about 1 ohm. A 120-foot length of the same wire has a resistance of about 2 ohms. Thus, if you double the length of the wire, you also double the resistance. In other words, the resistance of a conductor is directly proportional to its length. In fact, with any material, the greater the length, the higher the resistance. The reason for this is that the electrons must travel further through the resistance medium. Thus, if the length doubles, the resistance doubles; if the length triples, the resistance triples; and so forth.

Cross-Sectional Area. The cross-sectional area of a conductor is determined by its thickness or its diameter. You have seen that good conductors have a large number of free electrons. In fact, the more free electrons per unit of length, the better the conductor. Obviously then, a large diameter conductor has more free electrons per unit of length than a small diameter conductor of the same material. Therefore, large diameter conductors have less resistance than small diameter conductors.

All other things being equal, the resistance of a substance is inversely proportional to its cross-sectional area. If the cross-sectional area doubles, the resistance drops to one half its former value. Also, if the area triples, the resistance drops to one third.

Temperature. When resistivity is defined, the length and cross-sectional area are carefully defined because they affect resistance. The temperature is also carefully defined for the same reason. That is, with most materials, the resistance changes if the temperature changes. With changes in length and cross-sectional area, you know exactly how the resistance will change. Not only that, but all materials change resistance in the same way. However, with changes in temperature, this is not the case. Not all materials change resistance in the same direction or by the same amount when temperature changes.

In most materials, an increase in temperature causes an increase in resistance. Materials which respond in this way are referred to as having a *positive temperature coefficient*. If a material has a positive temperature coefficient, its resistance increases as temperature increases, and decreases as temperature decreases.

A few substances such as carbon have a *negative temperature coefficient*. This means that their resistance decreases as temperature increases. There are also materials whose resistances do not change at all with temperature. These materials have a zero or constant temperature coefficient.

In most simple circuits, the temperature coefficients of the components are not critical and are simply ignored. However, in some circuits temperature coefficients are important and you must be consider them in the design.

However, temperature characteristics are not always troublesome. A device called a *thermistor* uses these characteristics to great advantage. A thermistor is a special type of resistor which can achieve a large change in resistance for a small change in temperature. Such devices normally have a negative temperature coefficient. In many thermistors, the resistance value can drop to one half its former value for a temperature rise of 20 degrees centigrade. Thermistors are often used in temperature-sensing circuits and as protective devices in other types of circuits.

Resistance of Wire

You can find the resistance of a length of copper wire from the information in Table 3-1 (on the next page). The first column of this table shows the gauge of the wire. The diameter of each wire in this chart is 1.123 as large as the diameter of the succeeding wire. This is more obvious when you look at column two of the chart.

This column lists the actual diameter of each gauge wire in mils. A mil is equal .001 inches. If you look at #000 (pronounced "three aught") wire, you see that it has a diameter of 410 mils. Now if you multiply 410 mils times 1.123 you get the diameter of the next largest size wire; 460 mils for #0000 wire.

Column three contains the cross sectional area of each wire in circular mils. A circular mil is the area of a circle with the diameter of 1 mil.

Columns four and five are the resistances of 1000 ft of a given gauge of wire. Column four contains the resistance of the wire at 68°F, while in column five, the resistance values are given at 167°F. For example, 1000 ft of #9 wire has a resistance of .792 ohms at 68°F and .963 ohms at 167°F.

If you want to determine the resistance of a specific length of copper wire, you use the formula;

$$\frac{\text{Length of wire}}{1000} \times \text{Resistance of 1000 ft of wire}$$

For example, the resistance of 150 ft of #15 copper wire at 68°F is;

$$\frac{150\text{ ft}}{1000} \times 3.184\text{ ohms/1000 ft} = .48\ \Omega$$

Not all wire, however, is copper. Since each type of material has its own resistivity, you must adjust your resistance calculations according to the type of wire that you are using. You can do this by using the conversion factors given in Table 3-2.

If you look at this table, you see that the conversion factor for aluminum is 1.59. This means that resistance of aluminum wire is 1.59 times as great as the resistance of the same amount of copper wire. Therefore, if you use the calculations from the previous problem, you see that the resistance of 150 ft of #15 aluminum wire is;

$$.48\text{ ohms} \times 1.59 = .76\text{ ohms.}$$

In this way, you can determine the resistance of any of the types of wire shown in Table 3-2.

NUMBER	DIAMETER IN MILS	AREA IN CIRCULAR MILS	OHMS PER 1000 FT	
			COPPER ✱ 68° F	COPPER ✱ 167° F
0000	460	211,600	.049	.0596
000	410	167,800	.0618	.0752
00	365	133,100	.078	.0948
0	325	105,500	.0983	.1195
1	289	83,690	.1239	.151
2	258	66,370	.1563	.190
3	229	52,640	.1970	.240
4	204	41,740	.2485	.302
5	182	33,100	.3133	.381
6	162	26,250	.395	.481
7	144	20,820	.498	.606
8	128	16,510	.628	.764
9	114	13,090	.792	.963
10	102	10,380	.999	1.215
11	91	8,234	1.260	1.532
12	81	6,530	1.588	1.931
13	72	5,178	2.003	2.44
14	64	4,107	2.525	3.07
15	57	3,257	3.184	3.87
16	51	2,583	4.016	4.88
17	45.3	2,048	5.06	6.16
18	40.3	1,624	6.39	7.77
19	35.9	1,288	8.05	9.79
20	32.0	1,022	10.15	12.35
21	28.5	810	12.8	15.6
22	25.4	642	16.1	19.6
23	22.6	510	20.4	24.8
24	20.1	404	25.7	31.2
25	17.9	320	32.4	39.4
26	15.9	254	40.8	49.6
27	14.2	202	51.5	62.6
28	12.6	160	64.9	78.9
29	11.3	126.7	81.8	99.5
30	10.0	100.5	103.2	125.5
31	8.93	79.7	130.1	158.2
32	7.95	63.2	164.1	199.5
33	7.08	50.1	207	252
34	6.31	39.8	261	317
35	5.62	31.5	329	400
36	5.00	25.0	415	505
37	4.45	19.8	523	636
38	3.96	15.7	660	802
39	3.53	12.5	832	1012
40	3.15	9.9	1049	1276

Table 3-1

Wire gauge chart.

ALUMINUM	1.59
BRASS	4.40
GOLD	1.38
IRON	6.67
LEAD	12.76
NICHROME	60.
NICKEL	7.73
PLATINUM	5.80
SILVER	0.92
STEEL	8.62
TIN	8.2
TUNGSTEN	3.2
ZINC	3.62

Table 3-2

Ratio of resistance of metals compared to copper.

Programmed Review

1. Resistance is defined as a property of a substance which opposes current flow. All substances oppose current flow to some extent. Therefore, all substances have some ____________ .

2. (resistance) The unit of resistance is the ohm. The ohm is defined as the resistance of a particular block of material which has a certain length and cross sectional area. However, a better way to define the ohm is in terms of voltage and current. If an emf of 1 volt causes a current of 1 ampere, then the resistance is ____________ .

3. (1 ohm) Resistivity is defined as the resistance of a one mil-foot section of a particular material at 20°C. A mil-foot section is a piece of the material that is one foot long and 0.001 inch (1 mil) in diameter. If the material is copper, the mil-foot section has a resistance of about 10.4 ohms. Thus, the ____________ of copper is about 10.4 ohms.

4. (resistivity) The resistivity determines if a substance is a conductor or an insulator. Substances with very low resistivity values are conductors. Most metals are good conductors. Thus, silver, copper, gold, aluminum, brass, and tin are examples of ____________ .

5. (conductors) Materials which have very high resistivity values are insulators. Some examples are glass, rubber, mica, and dry air. These substances have ____________ values billions of times higher than those of the conductors.

6. (resistivity) The reciprocal of resistance is conductance. Conductance is defined as the ease with which a substance allows current to flow. The unit of conductance is the mho. One ohm of resistance is equal to one mho of conductance. However, the higher the resistance, the lower the conductance becomes. Thus, 10 ohms of resistance equals 1/10 mho. Also, 100 ohms of resistance equals ____________ of conductance.

7. (1/100 mho or 0.01 mho) In addition to resistivity, the resistance of a substance is determined by the size, shape, and temperature of the material. The length is important because the greater the length, the ____________ the resistance.

8. (greater) The resistance is also determined by the cross sectional area. The greater the cross sectional area, the ____________ the resistance.

9. (smaller) Temperature is also important. Most materials have a positive temperature coefficient. This means that the resistance increases when the temperature ____________ .

10. (Increases) Other materials, such as carbon, have a negative temperature coefficient. In these materials, the resistance decreases when the temperature ____________ .

11. (increases) A special type of resistor which uses this characteristic to good advantage is called a ____________ .

12. (thermistor)

RESISTORS

A resistor is an electronic component which has a certain specified resistance. Of course, other types of components also have some resistance. But the resistor is designed specifically to introduce a desired amount of resistance into a circuit.

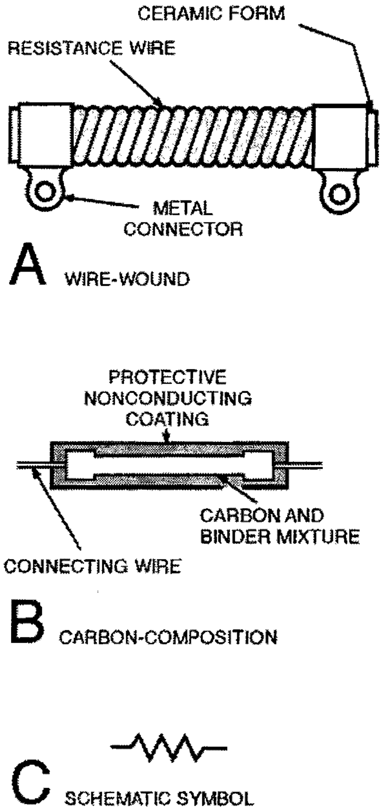
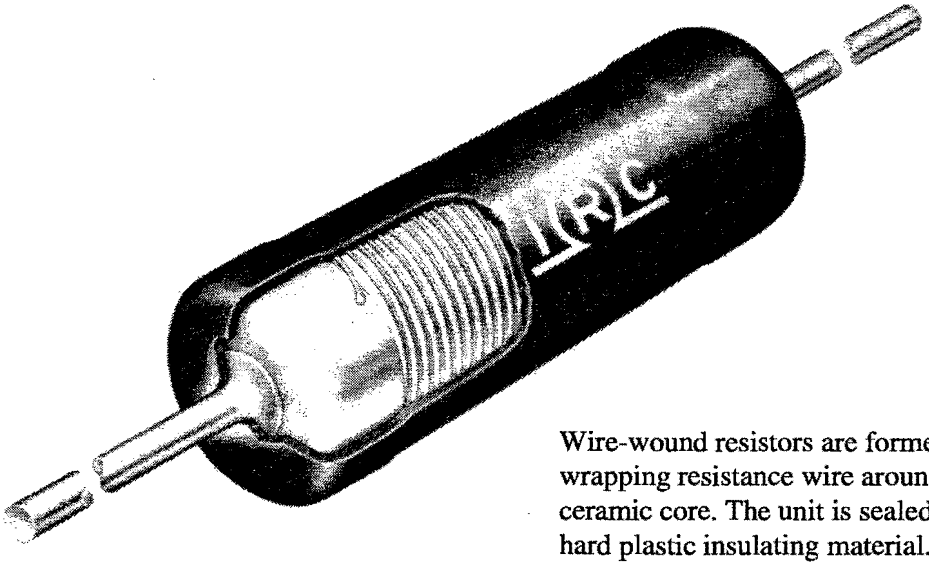

CERAMIC FORM
RESISTANCE WIRE
METAL CONNECTOR
A WIRE-WOUND
PROTECTIVE NONCONDUCTING COATING
CARBON AND BINDER MIXTURE
CONNECTING WIRE
B CARBON-COMPOSITION
C SCHEMATIC SYMBOL

Figure 3-3
Types of resistors and their schematic symbol.

Wire-Wound Resistors

You have seen that copper has a resistivity of about 10 ohms per mil-foot. You could wrap a one foot length of 1 mil diameter copper wire on an insulated form and attach contact leads as shown in Figure 3-3A. This would form a 10 ohm wire-wound resistor. The process for producing practical wire-wound resistors is a little more involved but the idea is the same.

The resistance wire used is generally a nickel-chromium alloy called nichrome which has a much higher resistivity than copper. The form is often a ceramic tube. After the leads are attached the entire resistor is covered with a hard protective coating. This type of resistor is often used in high current circuits where relatively high amounts of power must be dissipated. The resistance range can vary from less than an ohm to several thousand ohms. The wire-wound technique is also used to produce precise value resistors. Such precision values are required in meter circuits.



Wire-wound resistors are formed by wrapping resistance wire around a ceramic core. The unit is sealed by a hard plastic insulating material. (Courtesy IRC Division of TRW Inc.)

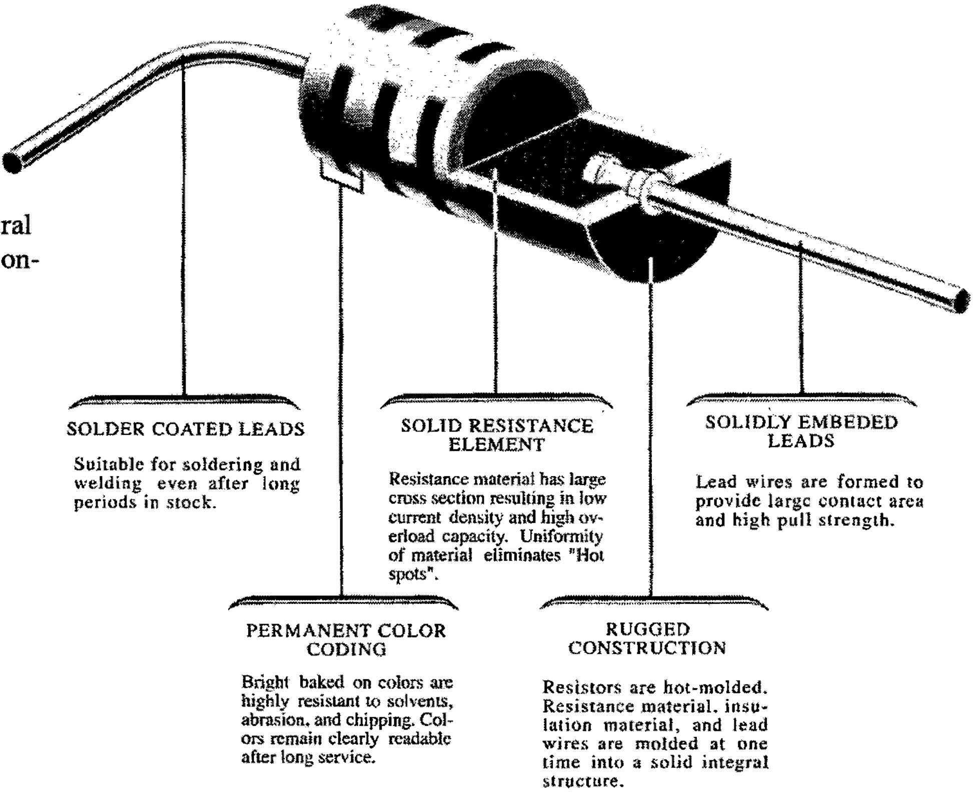
Carbon-Composition Resistors

The element carbon is neither a good conductor nor a good insulator. Instead, it falls between and is called a *semiconductor*. This makes carbon ideal as a material for resistors. By combining carbon granules and a powdered insulating material in various proportions, a wide range of resistor values are possible.

Figure 3-3B shows the construction of this type of resistor. Granules of carbon and a binder material are mixed together and shaped into a rod. Wire leads are inserted and the package is sealed with a non-conducting coating. The schematic symbol for the resistor is shown in Figure 3-3C.

Generally, carbon-composition resistors are used in low current circuits where they do not have to dissipate large amounts of power. Values can vary from 10 ohms or less to 20 megohms or more.

With the carbon composition resistor, the resistance value is indicated by color bands around the resistor. A chart that shows the color codes for over 160 standard value fixed resistors has been supplied with this Course. This chart can be used to determine the value of most any carbon-composition resistor you are likely to find. You will learn more about color codes later in this unit.



This cut-away view shows several desirable features of the carbon-composition resistor.
(Courtesy Allen-Bradley)

SOLDER COATED LEADS

Suitable for soldering and welding even after long periods in stock.

SOLID RESISTANCE ELEMENT

Resistance material has large cross section resulting in low current density and high overload capacity. Uniformity of material eliminates "Hot spots".

SOLIDLY EMBEDED LEADS

Lead wires are formed to provide large contact area and high pull strength.

PERMANENT COLOR CODING

Bright baked on colors are highly resistant to solvents, abrasion, and chipping. Colors remain clearly readable after long service.

RUGGED CONSTRUCTION

Resistors are hot-molded. Resistance material, insulation material, and lead wires are molded at one time into a solid integral structure.

Deposited-Film Resistors

Another popular type of resistor is the film-type resistor. The construction of this type of resistor is shown in Figure 3-4. In these devices, a resistance film is deposited on a nonconductive rod. Then the value of resistance is set by cutting a spiral groove through the film. This changes the appearance of the film to that of a long, flat ribbon spiralled around the rod. The groove adjusts the length and width of the ribbon so that the desired value is achieved. Several different types of deposited film resistors are available. The most common type is the carbon-film resistor. Here a carbon film is deposited on a ceramic rod. Several metal-film types are also available. One uses a nickel-chromium (nichrome) film on an aluminum oxide rod. Another uses a tin-oxide film on a glass rod.

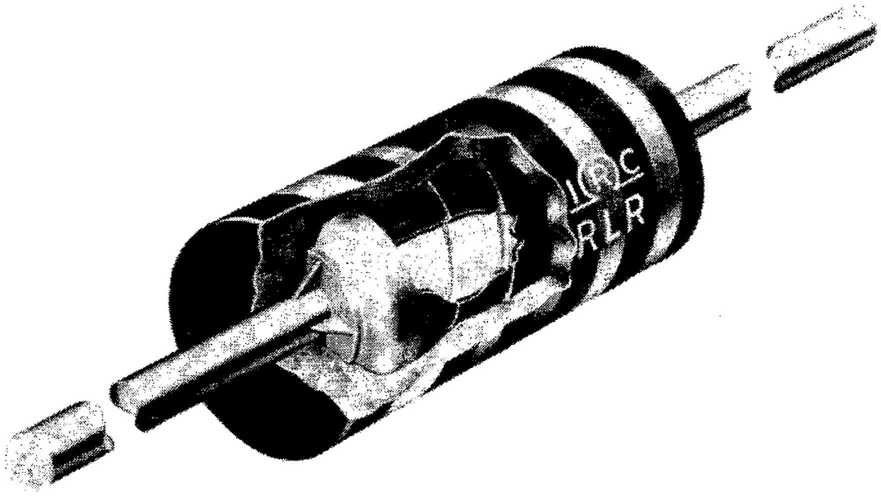


Figure 3-4
Deposited-film resistor.
(Courtesy IRC Division of TRW Inc.)

Resistor Ratings

Resistors have three very important ratings: resistance (in ohms), tolerance (in percent), and wattage (in watts). If you know what to look for, you can usually determine these ratings by simply examining the resistor. The following paragraphs describe each of these ratings in more detail.

Resistance. You learned about resistance in some detail already. You saw that it is determined by the length, the cross-sectional area, and the resistivity of the material used. With wire-wound resistors, the value is normally written somewhere on the resistor. However, with carbon-composition and film resistors, the value is usually indicated by color bands as shown on the chart supplied with this Course.

Tolerance. The resistance is rarely the exact value indicated on the resistor. It is extremely difficult and expensive to make the resistor the exact value indicated. For this reason, resistors have a tolerance rating. For example, a 1,000 ohm resistor may have a tolerance of ±5 percent. Five percent of 1000 is 50. Therefore, the actual value of the resistor can be anywhere from 950 ohms (1000 – 50) to 1050 ohms (1000 + 50).

Tolerances of ±5 percent, ±10 percent, and ±20 percent are common for carbon-composition resistors. Precision resistors often have a tolerance of +1 percent or better. Generally, the lower the tolerance, the more the resistor costs.

Wattage. Wattage rating refers to the maximum amount of power or heat that the resistor can dissipate without burning up or changing value. As shown in Figure 3-5, the larger the physical size of the resistor, the more power it can dissipate and the higher the wattage. Carbon-composition resistors generally have fairly low wattage ratings. Ratings of 2 watts, 1 watt, 1/2 watt, and 1/4 watt are the most common. Wire-wound resistors can have much higher wattage ratings. A rating as high as 250 watts is not too uncommon for wire-wound resistors.

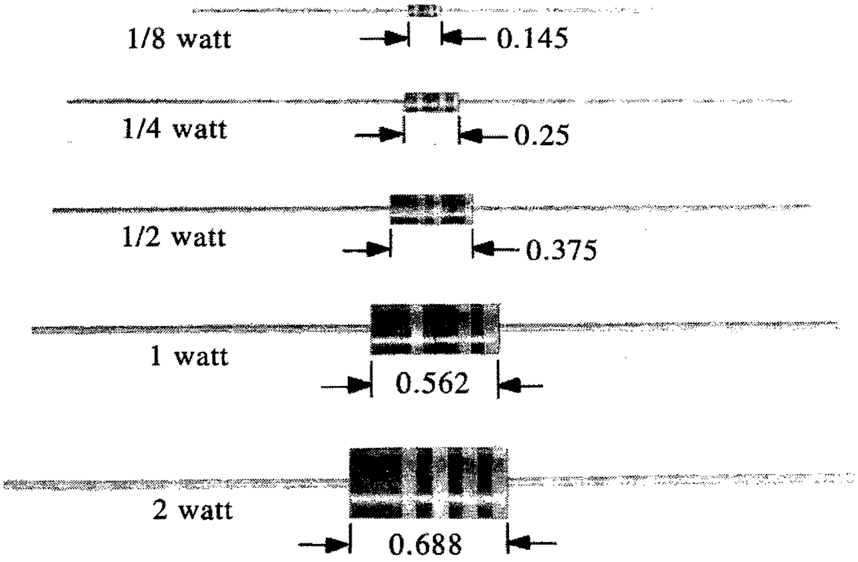


Figure 3-5

Dimensions in inches of Carbon-composition resistors. (Courtesy Allen-Bradley)

Chip Resistors

All of the resistors you learned about so far had leads (wires) so you can attach them to other circuitry. These leads take up a lot of real estate that is just not available in today's miniature electronic equipment, such as hand calculators, pocket games, laptop computers, etc. And manufacturers continue to cram more circuitry into a smaller space with every new model.

Figure 3-6 shows an internal view of a chip resistor that does not use leads. Instead, it has metal contacts on its ends that allow you to solder it directly to circuit board foils.

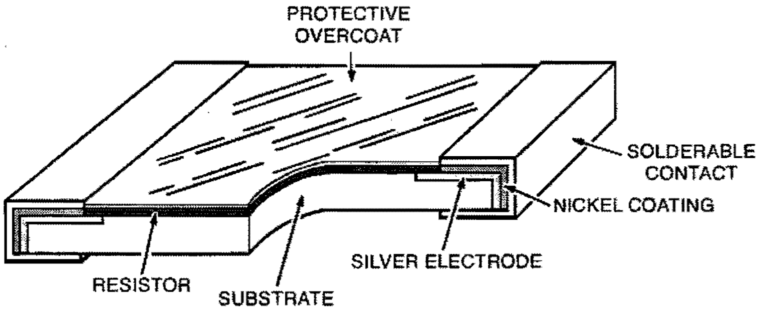


Figure 3-6
Internal view of a chip resistor.

An alumina (ceramic) substrate forms the foundation of the chip resistor. The substrate is first cut to the proper length, width, and thickness, depending upon the required value and power rating. Next, silver electrodes are attached to opposite ends of the substrate. A resistive paste or ink is then applied to the upper surface of the substrate and overlaps the electrodes. After this resistive material dries, it is baked to bond it to the substrate. A thin protective layer of glass protects the resistive material from becoming scratched, contaminated, or short-circuited.

Next, the exposed portions of the silver electrodes are coated with a thin film of nickel followed by a thin layer of solder. The nickel layer helps prevent the silver from slowly leaching away from the substrate.

Finally, solderable contacts are attached to the assembly so that the resistor can be easily connected to other circuitry. Chip resistors are used extensively in a manufacturing technique called surface mount technology (SMT).

Chip resistor sizes vary from 0.039" to 0.250" long × 0.019" to 0.125" wide × 0.014" to 0.025" thick.

Variable Resistors

The volume controls on television sets and radios are examples of variable resistors. These are resistors whose values you can change by simply rotating a shaft.

Figure 3-7A shows the construction of a variable carbon resistor. Figure 3-7B is a rearview of the inside of the device which shows how the resistance changes. A flat, circular strip of carbon is mounted between the two end terminals. A contact which moves along the resistance element connects to the center terminal. This arm is attached to the moveable shaft. If you move the arm in the direction shown by the arrow, the resistance between terminals 1 and 2 increases. Notice that, simultaneously, the resistance between terminals 2 and 3 decreases. This type of variable resistor is called a *potentiometer* or simply a *pot*. A potentiometer has three terminals.

A slight variation of this arrangement is called a *rheostat*. A rheostat has only two terminals. Thus, you can change a potentiometer into a rheostat by removing or not using terminal 3. Notice that the resistance between terminals 1 and 2 can still be varied without terminal 3. However, without the third terminal, the flexibility of the device is greatly reduced.

Wire-wound potentiometers are also common. Many have the same outward appearance as the potentiometer shown in Figure 3-7A. However, the internal construction is slightly different. As shown in Figure 3-7C, resistance wire is wound around an insulating core. A contact arm moves along the bare wire and changes the resistance between the center and outside terminals.

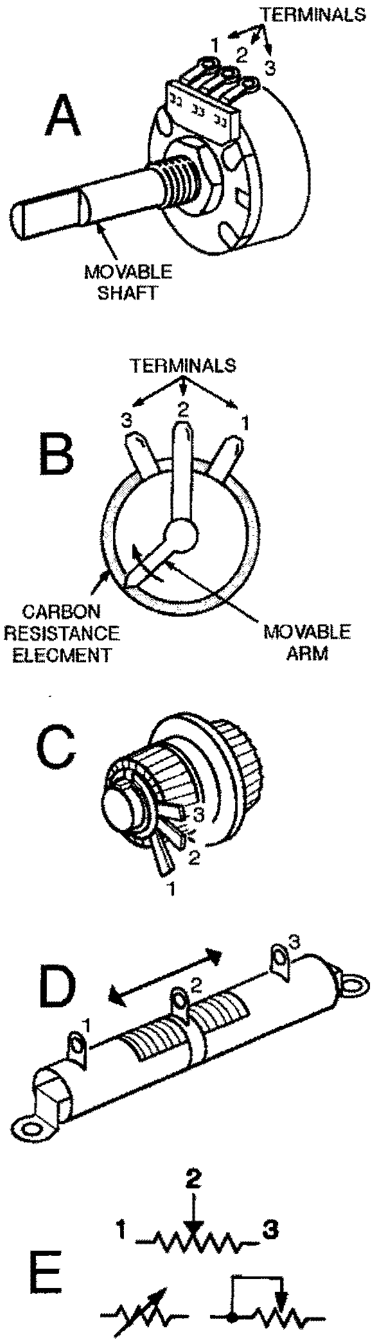
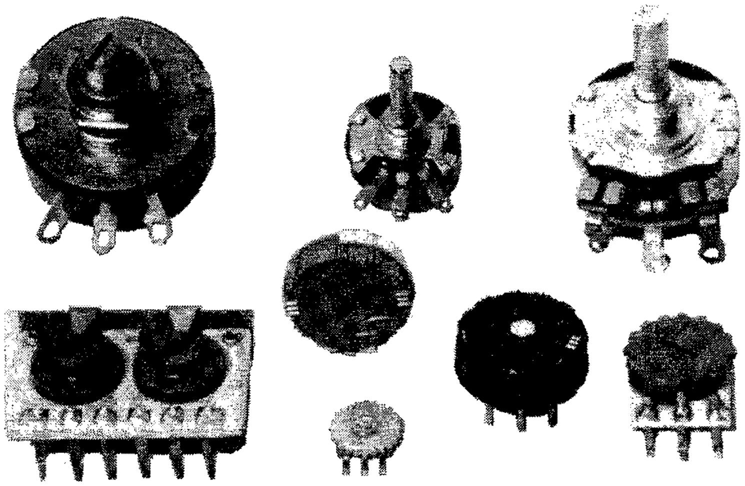


Figure 3-7
Variable resistors.



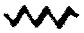
Potentiometers are available in a wide variety of shapes and sizes. (Courtesy Allen-Bradley)

Another type of variable resistor is shown in Figure 3-7D. This type is sometimes called a sliding-contact resistor. It is used in high-power applications where the resistance value must be initially set or occasionally reset. You can change the resistance value by moving the sliding contact along the bare resistance wire. Figure 3-6E shows schematic diagrams of variable resistors.

Programmed Review

13. A resistor is an electronic component designed to introduce a specific and desired amount of ____________ into a circuit.

14. (resistance) The three most popular types of resistors are carbon-composition, deposited-film, and wire-wound. The symbol for all three types of resistors is ____________ .

15. () Wire-wound resistors are formed by wrapping a length of resistance wire around a non-conducting form. A type of wire often used is an alloy of nickel and chromium called ____________ .

16. (nichrome) Wire-wound resistors generally have relatively low resistance values, but can have high-power ratings. Because their resistance value can be controlled very precisely, they are often used as ____________ resistors in meter circuits.

17. (precision) Carbon-composition resistors use a less complicated construction and are therefore less expensive. In these resistors, the resistance medium is a mixture of ____________ and a binder material.

18. (carbon) Due to their low price and wide resistance range, the carbon-composition and deposited-film resistors are the most popular types. However, its small physical size limits it to relatively low ____________ applications.

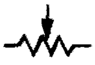
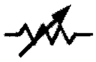
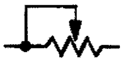
19. (power) Resistors have three important ratings which can usually be determined by examining the resistor. These are resistance, tolerance, and wattage. With carbon-composition and deposited-film resistors, the resistance and tolerance values are generally indicated by ____________ ____________ around the resistor.

20. (color bands) The wattage is indicated by the physical _______ of the resistor.

21. (size) Not all resistors have a permanently fixed value. Potentiometers, rheostats, and slide-wire resistors are examples of ____________ resistors.

22. (variable) The potentiometer and rheostat are often very similar in construction. However, you can always tell them apart because the ____________ has only two terminals, while the ____________ has three.

23. (rheostat, potentiometer) The symbol for the variable resistor is ____________.

24.  OR  OR 

CONNECTING RESISTORS

Resistors are often connected in series, in parallel, and in series-parallel combinations. In order to analyze and understand electronic circuits, you must be able to compute the total resistance of resistor networks.

Resistors In Series

As mentioned earlier, in a series circuit the components are connected end to end as shown in Figure 3-8A. Notice that the same current flows through all of the components. The current in the circuit must flow through all three resistors one after the other. Therefore, the total opposition to current flow is the total of the three resistances.

An example is shown in Figure 3-8B. Here three resistors are connected in series. The total resistance is called R_T and is the resistance across the entire series circuit. To determine R_T add the individual resistor values together. That is:

$$R_T = R_1 + R_2 + R_3$$
$$R_T = 10\ \Omega + 20\ \Omega + 30\ \Omega$$
$$R_T = 60\ \Omega$$

The three resistors in series have the same opposition to current flow as a single 60-ohm resistor.

This example used three resistors. However, the same principle holds true for any number of series resistors. Thus, in Figure 3-8C a 1 k ohm resistor in series with a 5 k ohm resistor has a total resistance of 6 k ohms or 6000 ohms. The circuit shown in Figure 3-8D uses six resistors. Some of the values are given in kilohms while others are given in ohms. To avoid confusion, convert all values to ohms. R_1, R_3, and R_5 are already expressed in ohms. R_2 is equal to 1 k ohms or 1000 ohms. R_4 is 1.2 k ohms or 1,200 ohms. And, R_6 is 3.3 k ohms or 3300 ohms. Thus, the total resistance, R_T, is:

$$R_T = R_1 + R_2 + R_3 + R_4 + R_5 + R_6$$
$$R_T = 500\ \Omega + 1000\ \Omega + 750\ \Omega + 1200\ \Omega + 600\ \Omega + 3300\ \Omega$$
$$R_T = 7350\ \Omega \text{ or } 7.35\ \text{k}\Omega$$

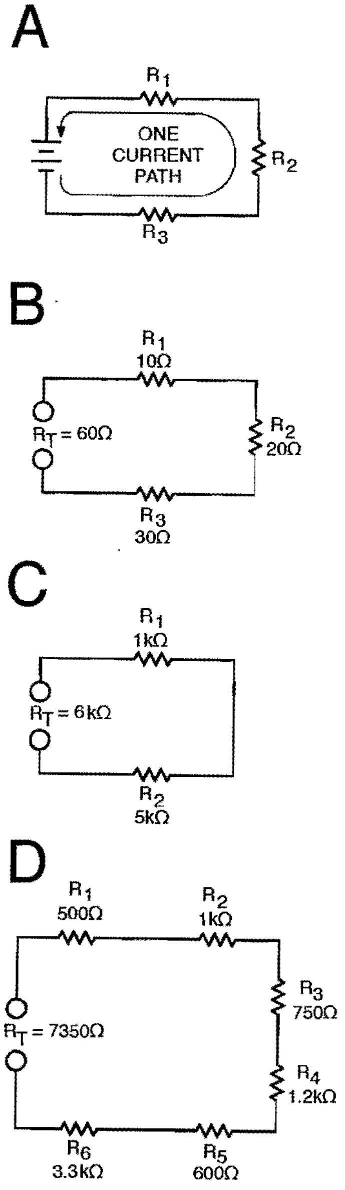


Figure 3-8
Resistors in series.

Resistors In Parallel

In parallel circuits, components are connected across each other so that there are two or more paths for current flow. Figure 3-9A is an example.

To see how resistors in parallel act, add switch S_1 in series with R_2 so that you can switch R_2 in and out of the circuit. The resulting circuit is shown in Figure 3-9B. With S_1 open, a certain current flows through R_1. The amount of current is determined by the resistance of R_1 and the applied voltage. Because there is only one path for current flow, the current through R_1 is the total circuit current.

Now close the switch and see what happens. The current through R_1 remains unchanged since neither the resistance of R_1 nor the applied voltage has changed. However, an additional current now flows through R_2. Thus, the total current provided by the battery increases. If R_2 has the same resistance as R_1, both resistors will offer the same amount of opposition to current flow. Thus, the current through R_1 equals the current through R_2. In this case, the current provided by the battery doubles when R_2 is switched in parallel with R_1.

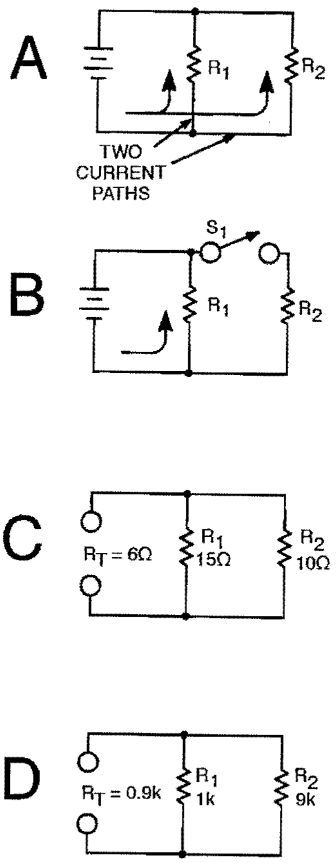


Figure 3-9
Resistors in parallel.

Regardless of the size of R_1 and R_2, the total current provided by the battery always increases when R_2 is placed in parallel with R_1 because a second current path is created. Obviously then, the total opposition to current flow decreases since more current now flows. Thus, when one resistor is placed in parallel with another, the total resistance decreases. Let's assume that R_1 and R_2 are equal. When the switch is closed, the total current doubles. Thus, the total resistance drops to one half of its former value.

There is a simple formula for finding the total resistance of two resistors in parallel. The formula is:

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

In Figure 3-9C, a 15-ohm resistor (R_1) is in parallel with a 10 ohm resistor (R_2). Find the total resistance R_T:

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

$$R_T = \frac{15\,\Omega \times 10\,\Omega}{15\,\Omega + 10\,\Omega}$$

$$R_T = \frac{150}{25}$$

$$R_T = 6\,\Omega$$

The total resistance of the circuit is the same as that of a 6 ohm resistor.

Figure 3-9D shows another example. Here, a 1 k ohm resistor is in parallel with a 9 k ohm resistor.

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

$$R_T = \frac{1000 \times 9000}{1000 + 9000}$$

$$R_T = \frac{9{,}000{,}000}{10{,}000}$$

$$R_T = 900 \text{ ohms or } 0.9 \text{ k ohms}$$

The above formula is normally used when two resistors are in parallel. However, it can be also used with three or more resistors. For example, Figure 3-10A shows four resistors in parallel. You can use the above formula to find an equivalent resistance for R_1 and R_2. Then, you can use the formula again to find an equivalent resistance for R_3 and R_4. Finally, you can apply the formula to the two equivalent resistances to find the total resistance. However, this method requires you to use the formula three different times.

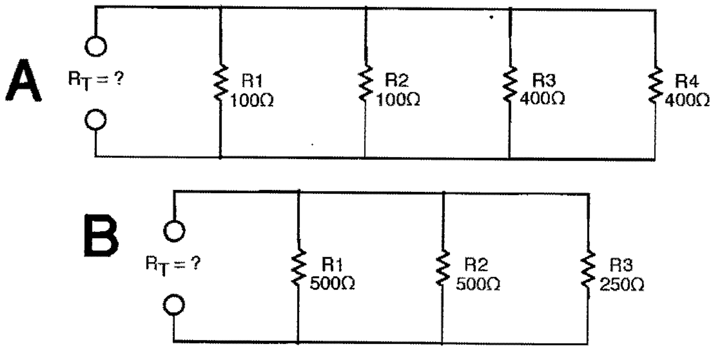


Figure 3-10

Compute the total resistance.

There is a better formula to use when more than two resistors are connected in parallel. The formula is:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} + \,..\, \frac{1}{R_n}}$$

Use this formula for the circuit shown in Figure 3-10A to find the total resistance (R_T):

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} + \,..\, \frac{1}{R_n}}$$

$$R_T = \frac{1}{\frac{1}{100} + \frac{1}{100} + \frac{1}{400} + \frac{1}{400}}$$

$$R_T = \frac{1}{.01 + .01 + .0025 + .0025}$$

$$R_T = \frac{1}{.025}$$

$$R_T = 40 \text{ ohms}$$

Figure 3-10B shows an example with only three resistors. Find R_T:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

$$R_T = \frac{1}{\frac{1}{500} + \frac{1}{500} + \frac{1}{250}}$$

$$R_T = \frac{1}{.002 + .002 + .004}$$

$$R_T = \frac{1}{.008}$$

$$R_T = 125 \text{ ohms}$$

Equal Resistors In Parallel

Sometimes two or more resistors which have the same value are connected in parallel. There is a simple rule which covers this situation. When all of the resistors in parallel have the same value, you can find the total resistance by dividing that value by the number of resistors in parallel. For example, Figure 3-11A shows two 20-ohm resistors connected in parallel. Our rule states that:

$$R_T = \frac{\text{value of one resistor}}{\text{number of resistors in parallel}}$$

$$R_T = \frac{20\ \Omega}{2}$$

$$R_T = 10\ \Omega$$

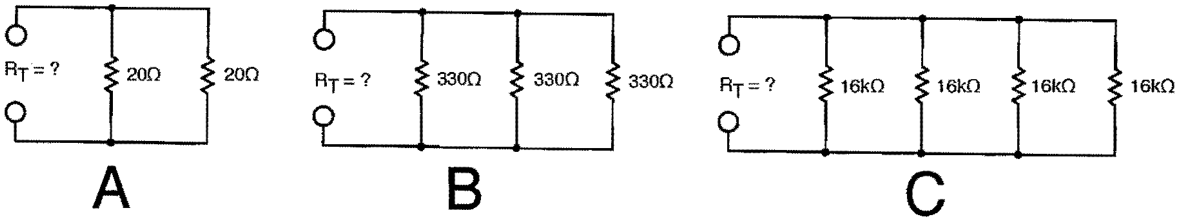


Figure 3-11
When all resistors have the same value, R_T equals the value divided by the number in parallel.

Likewise, when three resistors of the same size are connected in parallel, the total resistance is one third the value of one resistor. Thus, in Figure 3-11B:

$$R_T = \frac{330\ \Omega}{3}$$

$$R_T = 110\ \Omega$$

In Figure 3-11C

$$R_T = \frac{16\ \text{k}\Omega}{4}$$

$$R_T = 4\ \text{k}\Omega$$

Series-Parallel Connections

In many circuits, a parallel circuit is connected in series with one or more resistors as shown in Figure 3-12A. Even so, you can use the formulas shown earlier to easily calculate the total resistance. First, compute an equivalent resistance for the parallel circuit. Then, add this equivalent resistance to the series resistance values.

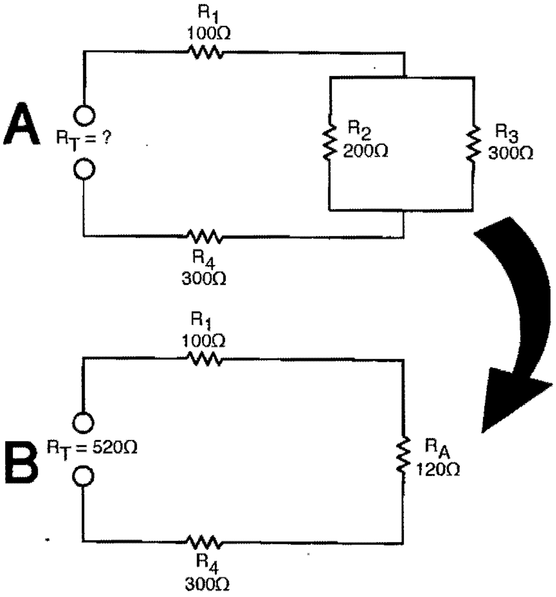


Figure 3-12
Simplifying the series-parallel circuit.

For example, first find the equivalent resistance for the parallel network made up of R_2 and R_3. Call this equivalent resistance R_A. Use the formula for a two-resistor parallel network, we find:

$$R_A = \frac{R_2 \times R_3}{R_2 + R_3}$$

$$R_A = \frac{200 \times 300}{200 + 300}$$

$$R_A = \frac{60{,}000}{500}$$

$$R_A = 120 \text{ ohms}$$

Now substitute R_A for the parallel network as shown in Figure 3-12B. Once you have the circuit in this simplified form, use the formula for finding the total resistance in a series circuit:

$$R_T = R_1 + R_A + R_4$$

$$R_T = 100\,\Omega + 120\,\Omega + 300\,\Omega$$

$$R_T = 520\,\Omega$$

The circuit shown in Figure 3-13A is an example of a more complex series-parallel circuit. In order to determine the resistance of this circuit, you must first simplify the circuit. The first step is to use the two-resistor parallel network formula to determine the equivalent resistance of the parallel network made up of R_2 and R_3. Call this equivalent resistance R_A:

$$R_A = \frac{R_2 \times R_3}{R_2 + R_3}$$

$$R_A = \frac{400 \times 100}{400 + 100}$$

$$R_A = \frac{40000}{500}$$

$$R_A = 80 \text{ ohms}$$

Now look at Figure 3-13B. Add the value of R_A to R_1 to find the resistance of the one leg of the branch formed by resistors R_1, R_2, and R_3. Call the resistance of this leg R_B:

$$R_B = R_A + R_1$$

$$R_B = 80 + 120$$

$$R_B = 200 \text{ ohms}$$

Now, determine the equivalent resistance of the parallel network made up of R_B and R_4 as shown in Figure 3-13C. This time use the equation for resistors having the same value in parallel. Call this resistance R_C. The resistance is:

$$R_C = \frac{\text{Value of one resistor}}{\text{Number of resistors in parallel}}$$

$$R_C = \frac{200}{2}$$

$$R_C = 100 \text{ ohms}$$

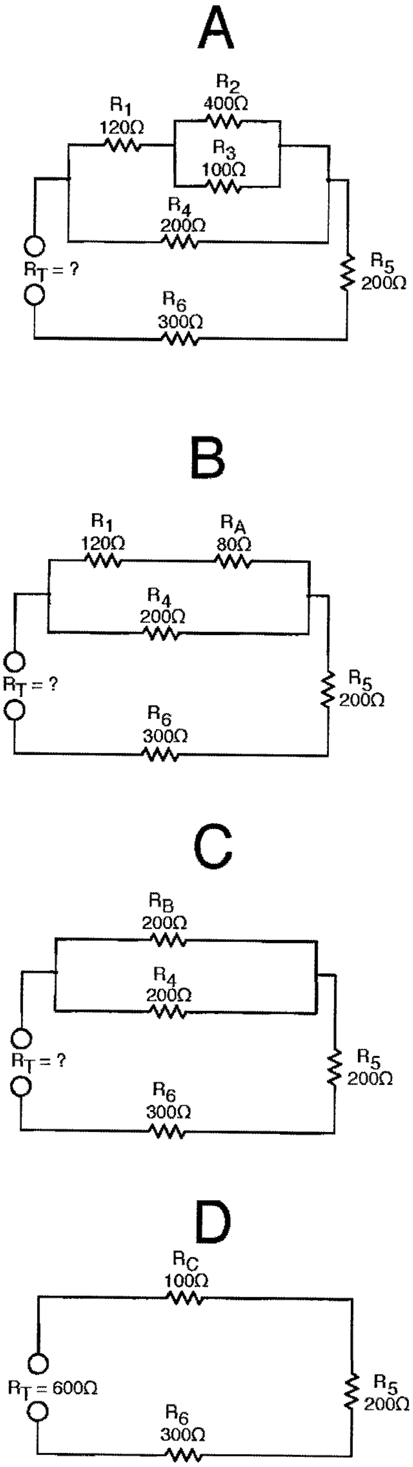

A
R1 120Ω
R2 400Ω
R3 100Ω
R4 200Ω
RT = ?
R5 200Ω
R6 300Ω
B
R1 120Ω
RA 80Ω
R4 200Ω
RT = ?
R5 200Ω
R6 300Ω
C
RB 200Ω
R4 200Ω
RT = ?
R5 200Ω
R6 300Ω
D
RC 100Ω
RT = 600Ω
R5 200Ω
R6 300Ω

Figure 3-13

Finally, you arrive at the circuit shown in Figure 3-13D. R_C is in series with resistors R_5 and R_6. In this simplified form, use the formula for total resistance in a series circuit to determine total resistance.

$$R_T = R_C + R_5 + R_6$$

$$R_T = 100 + 200 + 300$$

$$R_T = 600 \text{ ohms}$$

Programmed Review

25. Occasionally in electronics, you must calculate the total resistance of a series-parallel network. To solve for R_T in a network like that shown in Figure 3-14A, you must use the three formulas discussed in this section. The first step is to substitute an equivalent resistance for the parallel network made up of R_4, R_5, and R_6. If wyou call this equivalent resistance R_A, what is the formula for finding this resistance? R_A = ____________ .

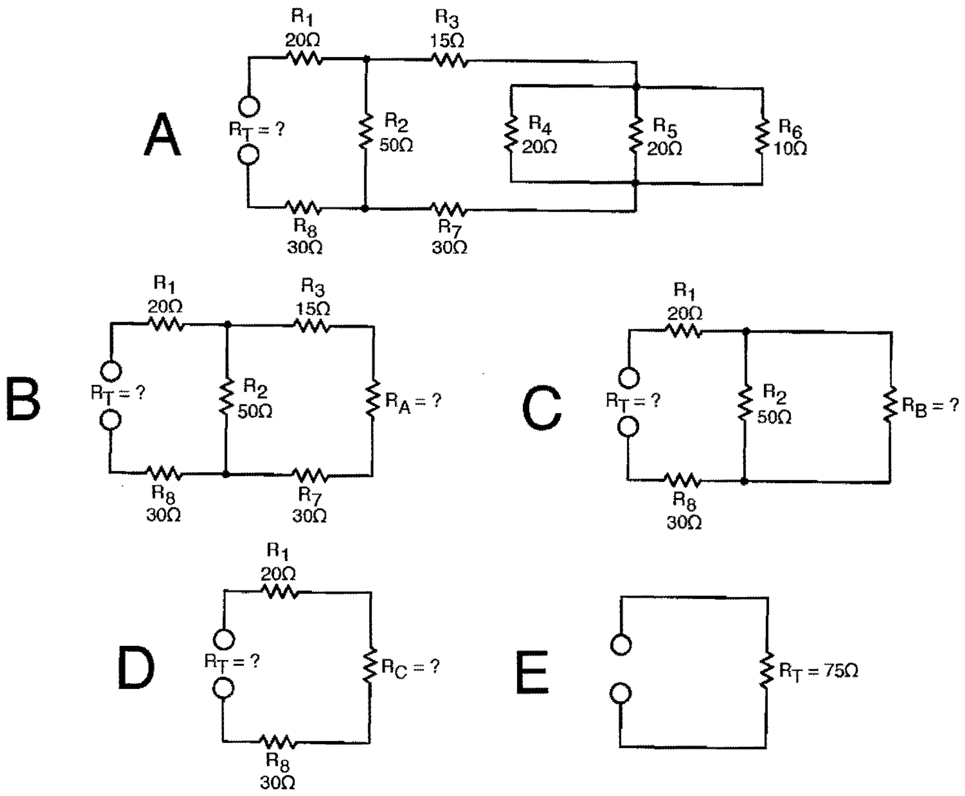

A
R1 20Ω
R3 15Ω
RT = ?
R2 50Ω
R4 20Ω
R5 20Ω
R6 10Ω
R8 30Ω
R7 30Ω
B
R1 20Ω
R3 15Ω
RT = ?
R2 50Ω
RA = ?
R8 30Ω
R7 30Ω
C
R1 20Ω
RT = ?
R2 50Ω
RB = ?
R8 30Ω
D
R1 20Ω
RT = ?
RC = ?
R8 30Ω
E
RT = 75Ω

Figure 3-14

Solving for total resistance in a complicated series-parallel network.

26. $\left[R_A = \dfrac{1}{\dfrac{1}{R_4} + \dfrac{1}{R_5} + \dfrac{1}{R_6}}\right]$ Substitute the values given and solve for R_A:

R_A is equal to ___________ ohms.

27. (5) Substituting R_A for the parallel network, the circuit is simplified as shown in Figure 3-14B. The next step is to find the equivalent resistance of the series network made up of R_3, R_A, and R_7. If you call this equivalent resistance R_B, the formula for finding R_B is ______________ .

28. ($R_B = R_3 + R_A + R_7$) Substitute the values given and solve for R_B. R_B is equal to ___________ ohms.

29. (50) Substituting R_B for the series network, the circuit is simplified again to the arrangement shown in Figure 3-14C. Notice that R_B is in parallel with R_2. The next step is to find the equivalent resistance of these two in parallel. If you call this equivalent resistance R_C, the formula for finding R_C becomes R_C = ___________ .

30. $\left[R_C = \dfrac{R_2 \times R_B}{R_2 + R_B} \text{ or } R_C = \dfrac{1}{\dfrac{1}{R_2} + \dfrac{1}{R_B}}\right]$ Use both formulas to solve for R_C. R_C is equal to ___________ ohms.

31. (25) If you now substitute R_C for the two parallel resistors, the circuit reduces to the simple series network shown in Figure 3-14D. You can now solve for the total resistance R_T. R_T is equal to ___________ ohms.

32. (75) Thus, as far as resistance is concerned, the network shown in Figure 3-13A has the same resistance as the circuit shown in Figure 3-14E.

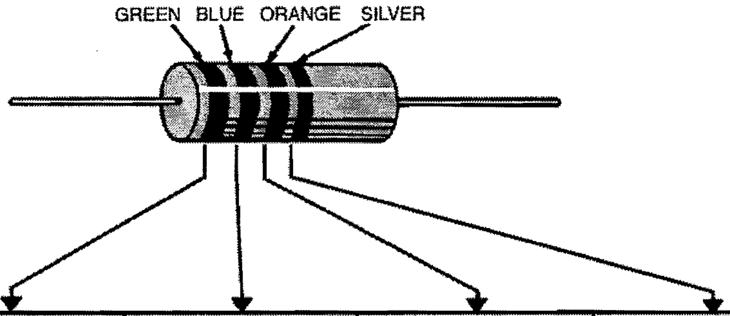
EXPERIMENT 5

Resistor Color Code

OBJECTIVE: *To learn to identify the value of a resistor from its color code.*

Introduction

The most common type of resistor used in electronics is the axial-lead thin film resistor. Axial-lead simply means that the leads run parallel to the resistor axis as shown in Figure 3-15 on the next page. The value in ohms of this type of resistor is indicated by color bands around one end of the resistor or by the value printed on the side of the resistor. The bands are a code that tells you the value, and the tolerance of that value. Depending upon the type of resistor, you will find four or five color bands painted on the body of the resistor. As a general rule, precision resistors, or resistors that are made to a nonstandard value, use a five-band coding system. Common or general purpose resistors use the four-band coding system. Figure 3-15 illustrates the 4-band color code system.



COLOR	BAND 1 FIRST NUMBER	BAND 2 SECOND NUMBER	BAND 3 MULTIPLIER	BAND 4 TOLERANCE
BLACK	0	0	1	
BROWN	1	1	10	
RED	2	2	100	
ORANGE	3	3	1,000	
YELLOW	4	4	10,000	
GREEN	5	5	100,000	
BLUE	6	6	1,000,000	
VIOLET	7	7	10,000,000	
GRAY	8	8	100,000,000	
WHITE	9	9	1,000,000,000	
GOLD			0.1	± 5%
SILVER			0.01	± 10%
NONE				± 20%

Figure 3-15

Color code for resistors.

To determine the resistance value in ohms, examine the color bands starting with the one closest to the end of the resistor. For example, assume that these bands are green, blue, orange, and silver. Use the following procedure to determine the value:

1. The first band indicates the first number in the resistance value. In the example the first band is green. Figure 3-15 tells you that the first number is 5.

2. The second band indicates the second number. The second band is blue. Figure 3-15 tells you that the second number is 6.

3. The third band indicates the multiplier. This indicates the number by which you must multiply the first two numbers. In the example, this band is orange so the multiplier is 1000.

4. Combining these numbers, you find that:

   First number = 5
   Second number = 6
   Multiplier = 1000

   Thus, the value is 56 × 1000 or 56,000 ohms (56 KΩ).

5. The fourth band indicates the tolerance of the resistor. This tells you how close to the actual value, the indicated value is. In the example, this band is silver. Thus, the tolerance is ±10 percent. This means that the actual value of the resistor is guaranteed to be 56,000 ohms ±10 percent. Ten percent of 56,000 is 5,600. Therefore, the actual value is between 50,400 ohms (56,000 – 5,600) and 61,600 ohms (56,000 + 5,600).

To be certain you understand the procedure, try another example. Suppose you have a resistor with three color bands of yellow, violet, and brown. Figure 3-15 tells you that the first two numbers are 47. The third color band (brown) tells you that the multiplier is 10. Thus, the value of the resistor is 47 × 10 or 470 ohms.

The absence of the fourth band indicates that the tolerance is ±20 percent. Twenty percent of 470 is 94. Thus, the actual value may be anywhere between 376 ohms (470 – 94) and 564 ohms (470 + 94).

A color code chart for both 4-band and 5-band resistors is provided with this Course.

Material Required

1 — Envelope labeled "RESISTORS FOR EXPERIMENT 5" or "R for Exp 5".

Procedure

1. Open the envelope and remove any one resistor.

2. List the color code of this resistor in the first four columns of Figure 3-16.

RESISTOR	FIRST COLOR	SECOND COLOR	THIRD COLOR	FOURTH COLOR	CODED VALUE (OHMS)	TOLERANCE %	MEASURED VALUE	WITHIN TOLERANCE
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								
19								
20								

Figure 3-16
Chart for Experiments 5 and 6.

3. From the first three bands, compute the coded value and enter this value under Coded Value (ohms).

4. From the fourth band, determine the tolerance and enter this number under Tolerance (percent). Do not complete the last two columns at this time.

5. Repeat the above steps for each of the 20 resistors provided in the envelope. Keep these resistors together because you will be measuring their values in the next experiment.

Discussion

The values of resistors provided with the Course are listed below. Of course, they are not in the same order as you have them listed in Figure 3-16.

470 ohms	5 percent	220 ohms	5 percent
1000 ohms	5 percent	560 ohms	5 percent
2200 ohms	5 percent	100 ohms	5 percent
4700 ohms	5 percent	33 k ohms	5 percent
15 k ohms	5 percent	220 k ohms	5 percent
10 ohms	5 percent	4700 ohms	5 percent
22 ohms	5 percent	15 ohms	5 percent
2200 ohms	5 percent	5100 ohms	5 percent
10 k ohms	5 percent	4.7 ohms	5 percent
1 M ohms	5 percent	10 M ohms	5 percent

No doubt, you noticed that some of the resistors are physically larger than the others. It is important to realize that the physical size has nothing to do with the ohmic value of the resistor. For example, compare the 10 ohm resistor with the 10 megohm* resistor. These two resistors have approximately the same physical size even though one has a resistance value 1 million times larger than the other.

The physical size of the resistor is an indication of the power that the resistor can dissipate. This is sometimes called *wattage.* The resistors supplied in this experiment are four distinct sizes: 2-watt, 1-watt, 1/2-watt, and 1/4-watt. In the next step, you will separate them according to their wattage.

* NOTE: Resistors that have values of much more than 10 megohms become increasingly more difficult to measure due to their high values. Obviously, this situation precludes determining whether the resistor is within tolerance with all but the most precise equipment.

Procedure (Continued)

6. Find the two resistors that are physically larger than all the others. Their large size indicates that these are two-watt resistors. From their color code, you know that their resistance values are __________ ohms and __________ ohms.

7. Find the 3 resistors of the next smaller physical size. These are one-watt resistors. Their resistance values are __________ ohms, __________ ohms, and __________ ohms.

8. Find the four smallest resistors. These are 1/4-watt resistors. Their resistance values are __________ ohms, __________ ohms, __________ ohms, and __________ ohms.

9. Examine the remaining 11 resistors. These are 1/2-watt resistors.

Discussion

The 2 watt-resistors have resistance values of 220 ohms and 100 ohms. Both have tolerances of 5 percent.

The 3 one-watt resistors have resistance values of 470 ohms, 1000 ohms, and 10 ohms. All have tolerances of 5 percent.

The four 1/4-watt resistors have values of 2200 ohms, 4700 ohms, 15 k ohms, and 560 ohms. All are 5 percent resistors.

All of the 1/2-watt resistors have a 5 percent tolerance.

NOTE: Due to improved manufacturing processes, most common resistors today have a tolerance of 5%. It is becoming increasingly difficult to find 10% and 20% resistors.

EXPERIMENT 6

Using the Ohmmeter

OBJECTIVE: *To learn to use the ohmmeter.*

Introduction

The device for measuring resistance is called an ohmmeter. Most multifunction meters contain an ohmmeter as well as a voltmeter. The characteristics of these meters vary greatly from one to the next. Therefore, you should carefully study the instructions provided with your particular instrument. You should become as familiar as possible with the ohmmeter function of your meter before you attempt this experiment.

There are some basic features which are common to most meter movement type ohmmeters. The following paragraphs describe these common features before you proceed with this experiment.

Resistance is read in ohms from a non-linear scale like the top scale shown in Figure 3-17. Zero ohms is at one end of the scale while infinite ohms is at the other. The meter shown in Figure 3-17 indicates 11 ohms. Actually, this reading is 11 ohms only if the range switch of the ohmmeter is on the R × 1 range. Most ohmmeters have a range switch for more accurate resistance readings over a wide range of resistor values. Ranges of R × 1, R × 10, R × 100, R × 1000, R × 10,000, R × 100,000, and R × 1,000,000 are common, although few meters are likely to have all these ranges. In the R × 1000 range, any reading you make from the scale needs to be multiplied by 1000. Thus, the reading in Figure 3-16 indicates 11,000 ohms or 11 k ohms.

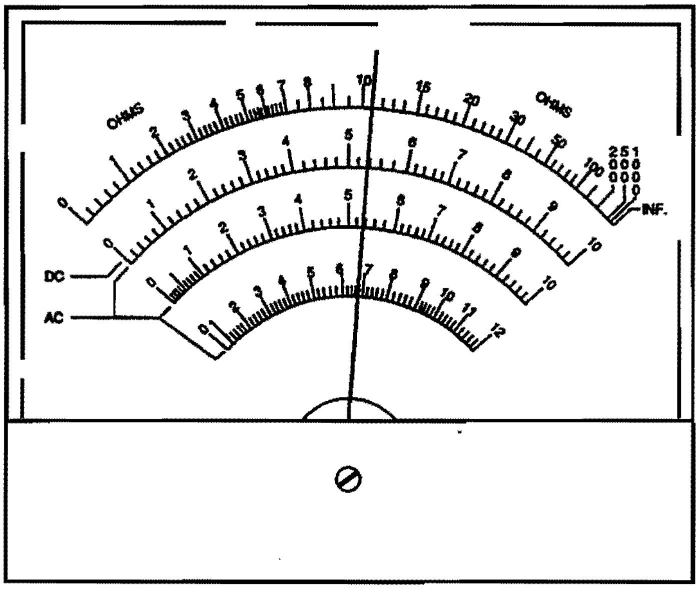


Figure 3-17

Resistance is read in ohms from the top scale of this particular meter.

In many ohmmeters, the scale is reversed with 0 ohms on the right and infinite ohms on the left. Some ohmmeters have a ZERO OHMS adjust. You must adjust the zero adjust anytime you change ranges on the meter. To make the adjustment, short the two test leads of the meter together and adjust it for exactly a 0-ohm reading on the meter. Many electronic type ohmmeters also have a full scale or infinite ohms adjustment. So once again you should check with the operating instructions of your particular meter to see how it should be set up to measure ohms. Modern digital meters do not require you to make zero or full-scale adjustments. Some do not even require you to set the range.

There is one more precaution. Never connect the ohmmeter to a circuit which has power applied. The sensitive circuitry in an ohmmeter can be damaged very easily if it is connected across a voltage source.

Material Required

20 — Assorted resistors from Experiment 5
1 — Ohmmeter (multimeter) with test leads.

Procedure

1. Measure the value of each of the resistors.
2. List the measured value in the column provided in Figure 3-16.
3. Use the coded value and the measured value to determine if each resistor is within the tolerance range. Indicate yes or no in the column provided.

Discussion

All of the measured values should fall within the tolerances indicated. Occasionally, a value may fall outside the tolerance range. However, this can be due to meter inaccuracies and to difficulties reading the scale. You should have noticed that resistors with the same color code had the same measured values. The larger the physical size of the resistor the more heat it can dissipate. Another way of saying the same thing is that the larger the physical size (not ohmic value) of a resistor the greater the current it can handle without burning up. Resistors that are rated over a half watt can get hot enough to cause a serious burn if you are not careful. It is usually a good idea not to touch electronic components once they are installed in a circuit and the circuit activated (turned on).

EXPERIMENT 7

Measuring Resistance Characteristics

OBJECTIVE: *To investigate the resistance characteristics of the potentiometer, thermistor, light bulb, and fuse.*

Introduction

All objects have resistance. In many objects, the resistance is so high that the ohmmeter always reads infinity. In others, the resistance is so low that the ohmmeter always reads zero. Most ohmmeters can indicate resistances as small as 1 ohm and as high as several megohms.

In this experiment, you will investigate the resistance characteristics of several different types of electronic components. As you learned earlier, the potentiometer is a variable resistor. Thus, its resistance can be changed by rotating a shaft. The thermistor is a temperature-sensitive resistance. Its resistance changes as its temperature changes.

Resistance is also important to other types of components which are not really resistors. For example, the light bulb or incandescent lamp could not work if it were not for its resistance. The resistance dissipates heat. The filament in the bulb heats to the point that it glows and gives off light. Another example is the fuse. The purpose of this device is to open when the current through it exceeds a certain level. The resistance of the fuse causes the fuse to open. A tiny resistance wire inside the fuse heats up as the current increases. When the critical current level is exceeded, the tiny wire heats to the point that it burns in two.

Material Required

1 — Heathkit Analog Trainer
1 — Ohmmeter (multimeter) with test leads
1 — 200 Ω potentiometer (#10-917)
1 — 120 Ω thermistor (#9-34)
1 — 100 kΩ thermistor (#9-182)
1 — Incandescent Lamp #49 (#412-16)
1 — Lamp Socket (#434-21)
1 — 1/16 amp fuse (#421-50)
1 Ft. — #22 nichrome wire
#22 copper wire
Soldering iron and solder

Figure 3-18 helps you identify these parts.

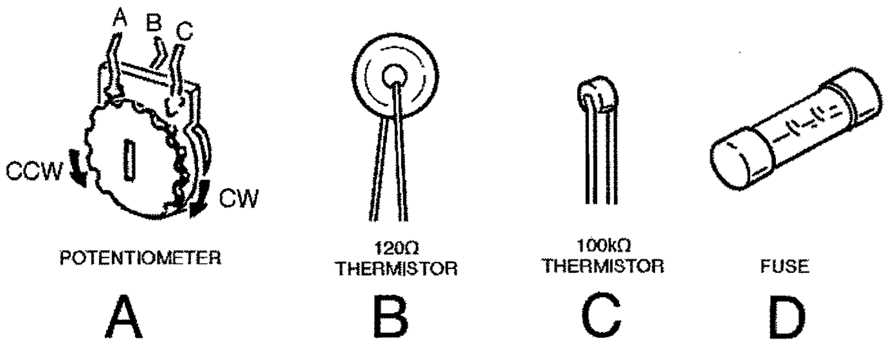


Figure 3-18

Some resistive devices.

Procedure

1. Examine the 200-ohm potentiometer. Turn it so that the knob is toward you. Use a pencil to label the three contacts A, B, and C as shown in Figure 3-18. You can write the letters directly on the fiber part of the potentiometer.

2. Rotate the knob of the potentiometer fully clockwise (cw). Use the ohmmeter to measure the resistance between contacts A and C. Call this resistance R_{AC}. R_{AC} = ____________ ohms. Rotate the knob of the potentiometer from the clockwise (cw) position to the counterclockwise (ccw) position. Did R_{AC} change? __________ . What assumption can you make about contacts A and C from these measurements? ____________________ .

3. Turn the knob fully ccw. Measure the resistance between A and B.
R_{AB} = ____________ ohms. Now turn the knob fully cw. The resistance
_________________ to ____________ ohms.
increased/decreased

4. Turn the knob fully ccw. Measure the resistance between B and C.
R_{BC} = ______ ohms. Turn the knob fully cw. The resistance _________________
to ____________ ohms. increased/decreased

5. Complete the following chart with the knob set to fully ccw, 1/4 cw, 1/2 cw, 3/4 cw, and fully cw positions.

KNOB SETTING	R_{AB}	R_{BC}	COMPUTE $R_{AB} + R_{BC}$
Fully ccw			
1/4 cw			
1/2 cw			
3/4 cw			
Fully cw			

6. Compute the total resistance from A to C by adding R_{AB} to R_{BC}. Fill in the final column of the chart with these computed values. Does the computed value always equal the value measured in Step 2? ____________. Can you think of an application for a simple circuit comprised of an ohmmeter and a potentiometer?

7. Set the potentiometer aside. Insert the 120 ohm thermistor into the socket of the Trainer as shown in Figure 3-19. Measure the resistance of the device. The resistance at room temperature is ___________ ohms.

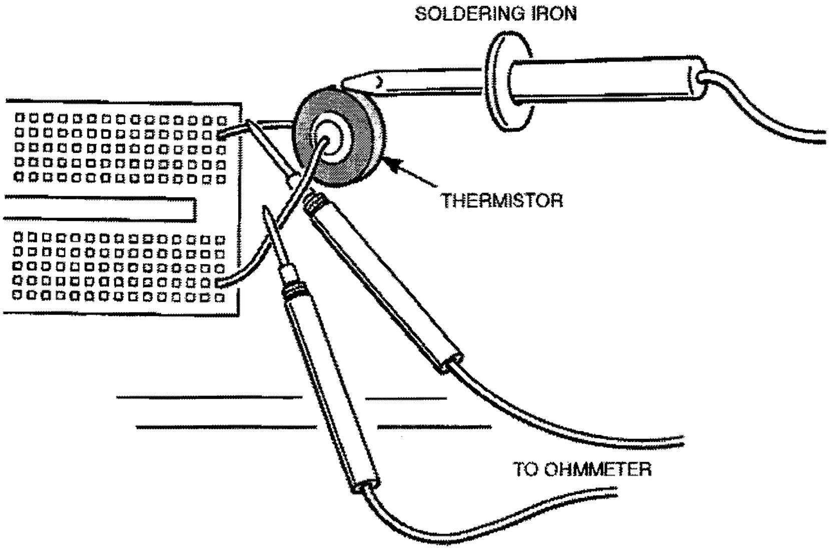


Figure 3-19
Checking the thermistor.

8. With the ohmmeter still attached, grasp the thermistor firmly between your thumb and forefinger to heat it. There should be a small but noticeable change in the resistance. The change will occur gradually as your fingers heat the thermistor.

9. Touch the black part of the thermistor with a low wattage (25 to 35 watts) soldering iron. As the thermistor heats up the resistance reading ________________ .
 increases/decreases

10. Hold the soldering iron against the thermistor until the resistance stops changing. The resistance at this time is ___________ ohms. Now remove the iron and notice the change in resistance.

11. Repeat steps 7, 9, and 10 using the 100 k ohm thermistor. At room temperature the resistance is ______ ohms. When heated the resistance ________________ to ____________ ohms.
increases/decreases

Can you think of an application for a circuit comprised of an ohmmeter and a thermistor?

12. Cut two three-inch lengths of wire. Strip 1/4-inch of insulation from the ends. Solder the leads to the lamp socket as shown in Figure 3-20. Insert the lamp into the socket. Connecting the ohmmeter across the socket leads and measure the resistance of the lamp . The resistance of the lamp is ____________ ohms. Did the lamp light when the ohmmeter was connected? __________
yes/no

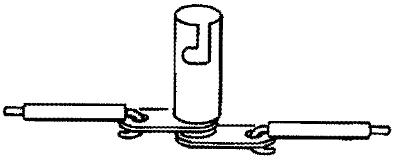


Figure 3-20

Solder leads to the lamp socket.

13. Examine the construction of the fuse. Notice how fragile the tiny wire is that connects between the two end terminals. Why is such a fragile wire used?

Measure the resistance of this wire. The resistance is ____________ ohms.

14. Use the information in Tables 3-1 and 3-2 on Page 3-12 to calculate the resistance of 1 foot of #22 copper wire and 1 foot of #22 nichrome wire. The resistance of the copper wire is ____________ ohms. The resistance of the nichrome wire is ____________ ohms.

15. Now, use your ohmmeter to determine the resistance of one foot of copper and nichrome wire. The resistance of the copper wire is ____________ ohms and the resistance of the nichrome wire is ____________ ohms.

Discussion

In this experiment, you examined the characteristics of several components. In steps 1 through 6 you measured the resistance between the various terminals of the potentiometer at a variety of knob settings. Figure 3-21 shows why your readings came out as they did. You saw that the resistance between contacts A and C (R_{AC}) is always constant. The reason for this is that these are the two end contacts of the potentiometer. Also, you saw that R_{AB} decreased as you turned the knob cw. The further cw that the knob is turned, the smaller R_{AB} becomes. The reason for this becomes obvious when you examine Figure 3-21. You saw that R_{BC} responds oppositely. This relationship between knob rotation and resistance can be put to good use.

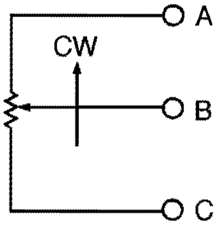


Figure 3-21
Schematic of a potentiometer.

Figure 3-22A shows a possible application of the potentiometer. Here, the knob is turned by a gear arrangement tied to a float in a fuel tank. By connecting the potentiometer in series with a battery and an ammeter, you can get an indication of the amount of fuel remaining in the tank. As shown, the tank is full and R_{AB} is near its minimum value. This allows maximum current to flow. Notice that the scale on the ammeter is marked to indicate the amount of fuel in the tank. As the fuel becomes used, the float drops, which turns the shaft of the potentiometer counterclockwise. This places more resistance in series with the battery and the meter. Consequently, less current flows through the meter. Thus, the meter reading gradually decreases as the fuel level drops lower and lower. Figure 3-22B shows the schematic diagram of this circuit. Notice that the dotted line indicates a mechanical connection between the float and the arm of R_1. This arrangement is generally used in schematics rather than showing the details of the mechanical connection.

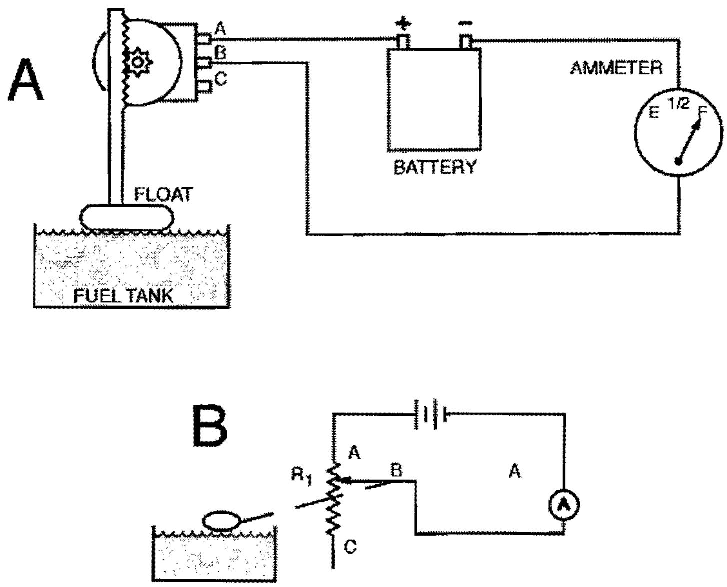


Figure 3-22
Typical application of a potentiometer.

In steps 7 through 11 you studied the resistance of two different types of thermistors. The first thermistor has a resistance of about 120 ohms at room temperature. This resistance drops to 20 ohms or less when it is heated with a soldering iron. The second thermistor has a much higher resistance. A resistance of about 100 k ohms is normal at room temperature. When it is heated, the resistance drops to about 20 k ohms or less. An obvious application of this device is a high temperature thermometer. It is easy to visualize the ohmmeter scale marked off in degrees rather than ohms. If the scale were properly calibrated in degrees, you could accurately measure temperature with the thermistor and the ohmmeter.

Finally, you measured the resistances of the incandescent lamp and the fuse. The resistance of the lamp is about 5 ohms (cold). At a current of about 60 milliamperes, this resistance dissipates enough heat to cause the lamp to glow brightly. Depending upon the type of ohmmeter used, the lamp may glow when you measure its resistance. The reason for this is that the ohmmeter has its own internal battery. With many ohmmeters, the current supplied by this battery is sufficient to cause the lamp to glow.

The resistance of the fuse is about 10 ohms. At a current of about 60 milliamperes the tiny wire inside the fuse heats up. If the current greatly exceeds 1/16 ampere (62.5 mA), the tiny wire burns in two and becomes an open circuit. Thus, it can be used to protect other, more expensive devices from current overloads.

In step 14 you calculated the resistance of the copper wire and the nichrome wire using the information from Tables 3-1 and 3-2. The resistance of the copper wire, from these calculations, is .0161 ohms while the resistance of the nichrome wire is about .966 ohms.

When you measured the resistance of the copper wire with the ohmmeter, you probably received an indication of zero resistance. This occurred because most ohmmeters are not designed to make measurements in the milliohm range. On the other hand, on the x 1 range of your ohmmeter, the resistance of the nichrome wire should have measured about 1 ohm. Here, however, the measurement may again vary significantly from 1 ohm because you are making your reading near the bottom of the scale.

The application of these two types of wire is based upon the difference in their resistivity. The copper wire is used where it is necessary to move current with the least amount of opposition. In almost all applications where a connection is needed between components in an electrical circuit, copper is used.

Nichrome wire is often used in wirewound resistors. Its high resistivity makes it ideal for this application. In addition, because nichrome wire has a high resistivity, like the tiny wire within the fuse, as the current through the nichrome wire increases so does the temperature of the wire. However, nichrome wire does not melt or burn through at a low temperature as does the wire in the fuse. For this reason, nichrome wire is used in applications where high heat is necessary. You can find nichrome wire in heater elements, or toaster coils.

EXPERIMENT 8

Light Dependent Resistor

OBJECTIVE: *To investigate the characteristics of the light dependent resistor (LDR).*

Introduction

The light dependent resistor (LDR) is also called a photo-resistor or a photoconductive cell. It is a special type of resistor which is sensitive to light. Its resistance changes as the light which falls upon it changes in intensity. This type of resistor has several applications in electronics.

Material Required

1 — Heathkit Analog Trainer
1 — Ohmmeter (multimeter) with test leads
1 — Incandescent lamp #49 (#412-16)
1 — Lamp socket (#434-21)
1 — Light dependent resistor (#9-83)
1 — 220 Ω, 5% 2-watt resistor (red-red-brown-gold)
1 — Roll of adhesive tape
#22 copper wire
Soldering iron and solder

Figure 3-23A helps you to identify the light dependent resistor. You also need a short length of tape (not supplied). This can be any kind of tape you find around the home

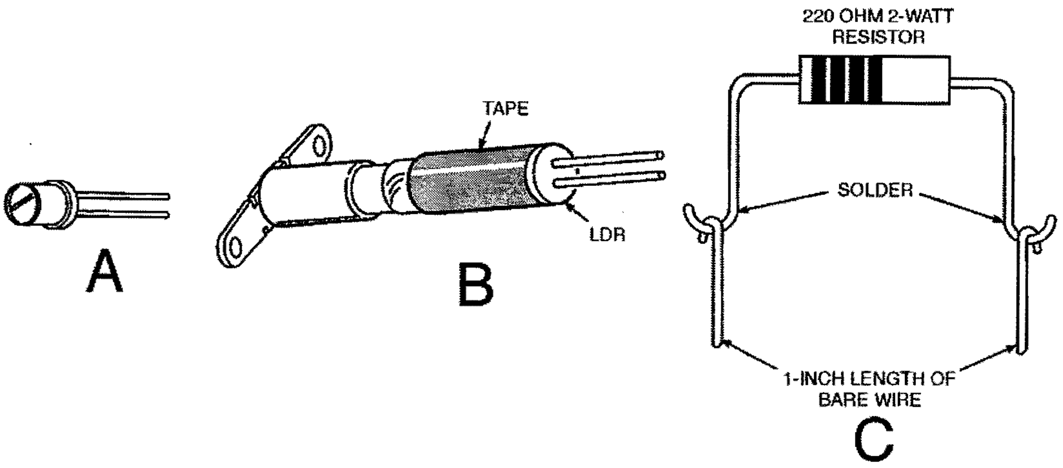


Figure 3-23
Preparing the LDR, lamp, and resistor.

Procedure

1. Connect the ohmmeter across the light dependent resistor (LDR). Measure the resistance at the normal light level in the room. The resistance is ____________ ohms. Hold your fingers over the end of the LDR to block light from falling on it. The resistance ______________ to ___________ ohms. Tape the
   increases/decreases
   light bulb to the LDR as shown in Figure 3-23B.

2. Since the leads of the 220 ohm, 2-watt resistor are too large to plug directly into the breadboard on the Trainer, you must attach smaller leads. Strip 2 inches of insulation from one end of the white hook-up wire. Cut off two 1-inch lengths of the bare wire. Solder a 1-inch bare wire to each lead of the 2-watt resistor as shown in Figure 3-23C.

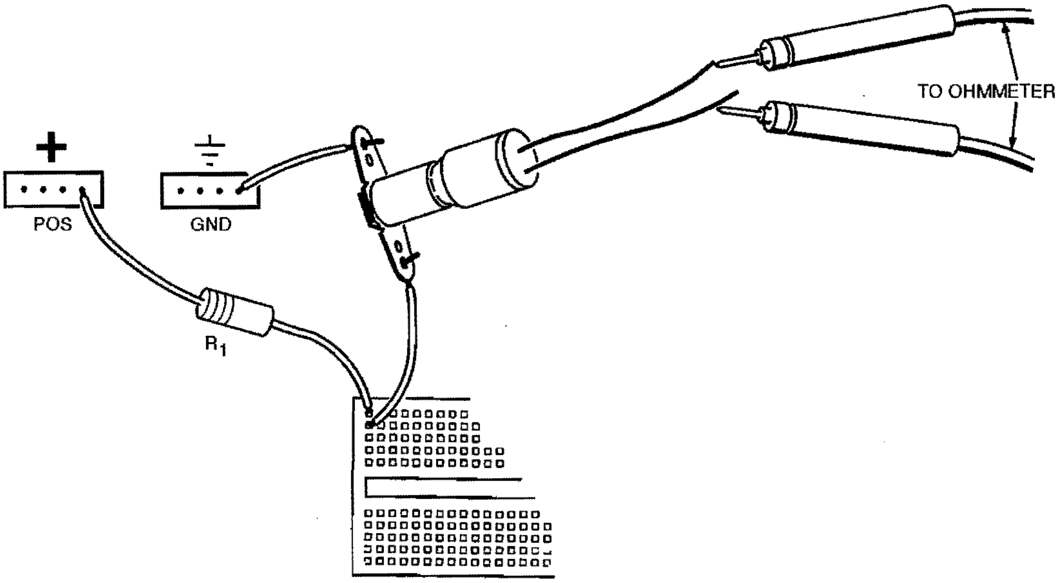


Figure 3-24
Light dependent resistor circuit.

3. Use the 220 ohm resistor, the ohmmeter, the lamp, and the LDR to construct the circuit shown in Figure 3-24. The schematic diagram of this circuit is shown in Figure 3-25. Note the schematic symbol for the ohmmeter and the LDR.

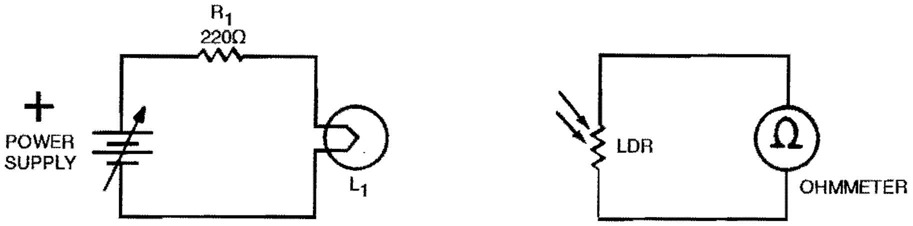


Figure 3-25

Schematic symbol of the circuit shown in Figure 3-24.

4. With the + voltage control set to minimum, switch the Trainer ON. The resistance of the LDR is ____________ ohms. Slowly increase the voltage until the lamp starts to glow. At this point the resistance of the LDR begins to

____________ .

increase/decrease

5. Continue to increase the voltage until the lamp is at maximum brightness. At this point the resistance of the LDR is ____________ ohms.

6. Leave the circuit connected while you carefully remove the tape and separate the LDR from the lamp. Tape the lamp to the top of the Trainer breadboard. Tape the LDR down so that its end is about 1/2 inch from the lamp as shown in Figure 3-26. Be certain that no tape is between the end of the lamp and the end of the LDR.

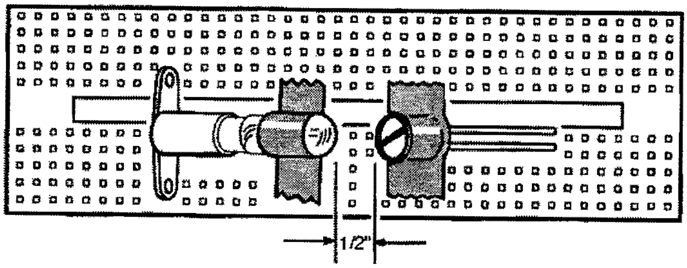


Figure 3-26

Tape the lamp and LDR about 1/2 inch apart on the breadboard.

7. Adjust the + voltage control so that the lamp glows at maximum brightness. The resistance of the LDR is ____________ ohms. Now place an obstruction such as your finger, a pencil, or a piece of paper between the lamp and the LDR. The resistance of the LDR changed to __________ ohms. Can you think of an application of a circuit such as this?

   ____

   ____

   ____

   ____

   ____

   ____

   ____

8. Switch the Trainer OFF.

Discussion

The LDR, or photoresistor changes resistance as the light level changes. At low light levels, the resistance is very high (hundreds of thousands of ohms in total darkness). However, as you saw in step 5, when the light level increases, the resistance falls to 10 k ohms or less. There are many applications for such a device. For example, some photographic light meters are little more than an LDR, battery, and current meter connected in series. The ammeter scale is often marked off in shutter speeds rather than milliamperes.

In Steps 6 and 7 you demonstrated a circuit which detects the presence or absence of an object between the light and the LDR. This technique is often used with burglar alarms, on automated assembly lines, in punched card and tape readers, and with doors which automatically open when a light beam is broken.

SUMMARY

Following is a summary of Unit 3.

Resistance is the opposition to current flow. The unit of resistance is the ohm. The ohm may be expressed in terms of voltage and current. It is equal to the amount of resistance which will allow one ampere of current to flow when an emf of 1 volt is applied. The Greek letter omega is used to represent the ohm.

Resistivity is defined as the resistance of one mil-foot length of a material at 20 degrees centigrade. A mil-foot is a one foot length of wire which is one thousandth of an inch in diameter. The resistivity determines if a material is an insulator or a conductor.

Most metals have a very low resistivity and are therefore good conductors. Some examples are silver, copper, aluminum, nickel, iron, lead, and gold. Other materials have values of resistivity billions of times higher. These materials are good insulators. Examples are glass, rubber, mica, and plastics.

The resistance of a material is determined not only by its resistivity but also by its size and shape. Resistance is directly proportional to the length of a conductor but inversely proportional to the cross-sectional area.

Temperature also affects resistance to some extent. If the resistance increases with temperature, the substance has a positive temperature coefficient. If the resistance decreases with temperature, the substance has a negative temperature coefficient.

There are three popular types of fixed resistors. These are: carbon-composition, wire-wound, and deposited-film. Carbon-composition resistors are the most common and least expensive while wire-wound resistors are the most expensive. Wire-wound resistors generally have relatively low resistance values, but they can have high power ratings. Deposited-film resistors fill the gap between composition and wire-wound resistors. They can be made more precise than composition resistors and they are cheaper than wire-wound resistors.

You can determine the resistance, tolerance, and wattage of most resistors by close examination of the resistor. With many wire-wound resistors, this information is written on the body of the resistor. With composition and film resistors, three color bands indicate the resistance. A fourth color band indicates the tolerance and the physical size of the resistor indicates the wattage.

Not all resistors have a fixed value; some are variable. A resistor whose value can be changed by rotating a shaft is called a potentiometer if it has three terminals, but is called a rheostat if it has only two terminals.

Resistors may be connected in series or in parallel. When they are connected in series, their resistance values add. Thus, if two 1000 ohm resistors are connected in series, the total resistance is 2000 ohms.

When resistors are connected in parallel, the total resistance decreases. If two 1000 ohm resistors are connected in parallel, the total resistance becomes 500 ohms.

An ohmmeter is a device that is used to measure resistance. Most ohmmeters have a nonlinear scale with 0 at one end and infinity at the other. A range switch is usually provided so that a wide range of resistance values can be accurately measured. A zero adjust is also included on some meters. This control must be readjusted each time you change the range.

All electronic components have some resistance value. The light bulb works only because of the resistance of its filament. It is this resistance that produces the heat which causes the filament to glow. The fuse is another example. Here a fragile length of resistance wire is designed to burn in two when the current rating is exceeded.

The thermistor is a special type of resistor whose resistance value changes with temperature. The light dependent resistor or photoconductive cell is a resistor whose value changes when it is exposed to light. Both of these devices are used as control elements in electronics.

UNIT EXAMINATION

1. An ohm is the amount of resistance which allows:

   A. one ampere of current to flow when one volt of emf is applied.
   B. one coulomb of current per second to flow.
   C. one ampere of current to flow through a one mil-foot section of #22 copper wire.
   D. one ampere of current to flow through a one mil-foot column of mercury.

2. A resistance of 20 ohms equals a conductance of:

   A. 20 ohms.
   B. 20 mhos (siemens).
   C. .05 ohms.
   D. .05 mhos (siemens).

3. Resistivity is the resistance of:

   A. a column of mercury 106.3 centimeters high and 1 millimeter square.
   B. a length of #22 copper wire which is 60 feet long.
   C. a one mil-foot length of a substance at 20°C.
   D. a substance which has a conductance of 1 mho.

4. The resistance of an insulated wire is determined by its:

   A. resistivity, length, temperature, and type of insulation.
   B. size, shape, and applied voltage.
   C. length, cross-sectional area, resistivity, and temperature.
   D. cross-sectional area, length, current-carrying capability.

5. The resistance of a conductor is:

   A. directly proportional to its length and inversely proportional to its cross-sectional area.
   B. directly proportional to both its length and its cross-sectional area.
   C. inversely proportional to both its length and its cross-sectional area.
   D. inversely proportional to its length and directly proportional to its cross-sectional area.

6. The resistance of a certain substance increases when the temperature increases. Therefore, this substance has a:

   A. negative temperature coefficient.
   B. positive temperature coefficient.
   C. zero temperature coefficient.
   D. constant temperature coefficient.

7. The physical size of a resistor is an indication of its:

   A. Resistance.
   B. Tolerance.
   C. Power dissipation capability.
   D. Resistivity.

8. A resistor has three red bands. Its value is:

   A. 222 ohms.
   B. 220 ohms.
   C. 2200 ohms.
   D. 0.22 ohms.

9. The fourth band of a 1 K ohm resistor is gold. The actual resistance may be anywhere between:

   A. 900 ohms and 1100 ohms.
   B. 950 ohms and 1050 ohms.
   C. 800 ohms and 2000 ohms.
   D. 990 ohms and 1010 ohms.

10. What is the total resistance (R_T) of the resistor network shown in Figure 3-27?

   A. 15 ohms.
   B. 5 ohms.
   C. 10 ohms.
   D. 20 ohms.

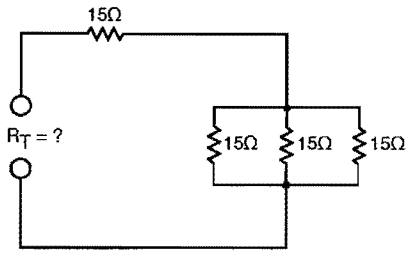


Figure 3-27
Circuit for Question 10.

11. Which of the following shows the proper method for measuring the resistance of R_1?

    A. Figure 3-28A.
    B. Figure 3-28B.
    C. Figure 3-28C.
    D. Figure 3-28D.

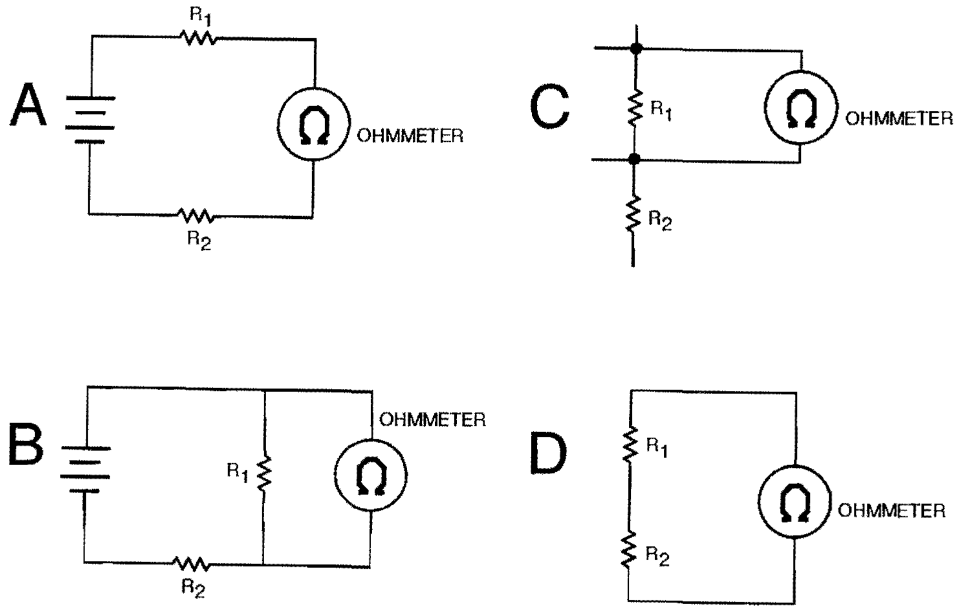

A
R1
R2
Ω
OHMMETER
C
R1
R2
Ω
OHMMETER
B
R1
R2
Ω
OHMMETER
D
R1
R2
Ω
OHMMETER

Figure 3-28

Circuits for Question 11.

12. The band nearest one end of a resistor is yellow. The next is violet and the third is orange. The fourth is gold. Which of the following is within the tolerance rating?

    A. 49.3 k ohms.
    B. 450 ohms.
    C. 473 ohms.
    D. 43 ohms.

Use Tables 3-1 and 3-2 on Page 3-12 when you answer the next two questions.

13. What is the resistance of 300 ft of #22 copper wire at 67°F?

   A. .48 ohms.
   B. 4.83 ohms.
   C. 48.3 ohms.
   D. 483 ohms.

14. What is the resistance of 500 ft of #30 tungsten wire at 67°F?

   A. 1.65 ohms.
   B. 16.5 ohms.
   C. 165 ohms.
   D. 1650 ohms.

15. Another name for resistivity is:

   A. mass.
   B. valence.
   C. specific resistance.
   D. tolerance.

16. If a resistor is added, in series to an existing circuit, the resistance of the circuit will:

   A. decrease.
   B. increase.
   C. remain the same.
   D. Either A or B depending upon the size of the resistor.

17. Which of the following is NOT a type of fixed resistor?

   A. Wire-wound resistor.
   B. Carbon-composition resistor.
   C. Ceramic-disc resistor.
   D. Deposited-film resistor.

18. As the diameter of a conductor increases, the resistance of the conductor:

   A. increases.
   B. decreases.
   C. remains the same.

19. As the length of a conductor increases, the resistance of the conductor:

    A. increases.
    B. decreases.
    C. remains the same.

20. As the temperature of a material increases, the resistance of the material:

    A. increases.
    B. decreases.
    C. increases if the material has a positive temperature coefficient.
    D. decreases if the material has a positive temperature coefficient.

21. A change in ___________ causes the resistance of a thermistor to change.

    A. light
    B. temperature
    C. humidity
    D. altitude

22. A change in ___________ causes the resistance of an LDR to change.

    A. light
    B. temperature
    C. humidity
    D. length

23. If one volt of emf causes one ampere of current to flow in a circuit, the resistance of the circuit is:

    A. .1 ohm.
    B. 1 ohm.
    C. 10 ohms.
    D. 100 ohms.

24. When you use an ohmmeter to check the resistance of a resistor that is part of a circuit:

    A. you must observe the polarity of the resistor.
    B. the resistor must remain in the circuit.
    C. you must remove the resistor from the circuit.

25. Which of the following statements is true?

    A. The resistance of a conductor is, in general, very high.
    B. The resistance of an insulator is, in general, very low.
    C. Insulators have large numbers of free electrons.
    D. Conductors have large numbers of free electrons.

EXAMINATION ANSWERS

1. A — The ohm is most often defined in terms of voltage and current. It is the amount of resistance which allows one ampere of current to flow when one volt of emf is applied.

2. D — Conductance is the reciprocal of resistance. Thus,

$$\text{Conductance (mhos or siemens)} = \frac{1}{\text{Resistance (ohms)}}$$

Therefore, if the resistance is 20 ohms:

$$\text{conductance} = \frac{1}{20}$$

$$\text{conductance} = .05 \text{ mhos or siemens.}$$

3. C — Resistivity is the resistance of one mil-foot wire of the substance at 20°C.

4. C — The resistance of any material is determined by its length, cross-sectional area, resistivity, and temperature.

5. A — The resistance of a conductor is directly proportional to its length and inversely proportional to its cross-sectional area.

6. B — If resistance increases when temperature increases, the substance has a positive temperature coefficient.

7. C — The larger the resistor, the more power it can dissipate.

8. C — The first two red bands tell you that the first two numbers are 22.

9. B — Gold represents a tolerance of 5 percent. Now, 5 percent of 1000 ohms is 50 ohms. Therefore, the value can be anywhere between 950 ohms (1000 – 50) and 1050 ohms (1000 + 50).

10. D — When you use the formula for parallel resistors, you find that the total resistance for the three 15 ohm resistors in parallel is 5 ohms. This 5 ohms of resistance is in series with the remaining 15 ohm resistor. Thus, the total resistance is 20 ohms.

11. C — Answers A and B demonstrate a connection which you should never attempt. That is, the ohmmeter should never be connected to a circuit which has power applied. Damage to the meter may result. Answer D shows how to measure the total resistance of R_1 and R_2. Answer C shows the proper way to measure R_1. Notice that the meter is connected directly across R_1 so that the current from the meter flows through only R_1.

12. A — The color code indicates a 47 k ohm 5 percent resistor. Of the answers listed, only 49.3 k ohms falls within this range.

13. B — The resistance of 1000 ft of #22 copper wire is 16.1 ohms. You can find this value in Table 3-1. Now use the equation:

$$\frac{\text{Length of wire}}{1000} \times \text{Resistance of 1000 ft of wire}$$

to determine the resistance of 300 ft of wire.

$$\frac{300}{1000} \times 16.1 = 4.83 \text{ ohms}$$

14. C — Again, you first find the resistance of 1000 ft of #30 copper wire at 67°F. This value is 103.2 ohms. Now use the equation:

$$\frac{500}{1000} \times 103.2 = 51.6 \text{ ohms}$$

This gives you the resistance of copper wire. Now you find the conversion factor for tungsten in Table 3-2. Then you compute the resistance of the tungsten wire like this:

$$51.6 \text{ ohms} \times 3.2 = 165.12 \text{ ohms or } 165 \text{ ohms}$$

15. C — Another name for resistivity is specific resistance.

16. B — To determine resistance in series, you add the values of the resistors in the circuit. Therefore, when you place another resistor in a circuit, no matter how small the resistor is, the total resistance of the circuit will increase.

17. C — The ceramic disc is not a type of fixed resistor.

18. B — The resistance of a conductor decreases as the diameter of the conductor increases.

19. A — As the length of a conductor increases, the resistance of the conductor also increases.

20. C — When temperature increases, the resistance of some materials will increase. These materials have positive temperature coefficients. In other materials, the resistance decreases with a rise in temperature. These materials have negative temperature coefficients.

21. B — Thermistors are variable resistors that are sensitive to heat.

22. A — LDRs are variable resistors that are sensitive to light.

23. B — When one volt of emf is applied to a circuit that has one ohm of resistance, one ampere of current will flow through the circuit.

24. C — Whenever an ohmmeter is used to check the resistance of a component, it is necessary to remove the component from the circuit. If you do not do this, the circuit itself will effect the resistance shown on the meter.

25. D — Conductors have large numbers of free electrons. For this reason, current flows easily through conductors. Since there is little opposition to current flow through a conductor, the conductor has a low resistance.

UNIT 4

OHM'S LAW

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INTRODUCTION

Ohm's Law is the most important and most basic law of electricity and electronics. It defines the relationship between the three fundamental electrical quantities: current, voltage, and resistance. Fortunately, the relationship between these three quantities is quite simple. Several implications of this relationship have already been discussed in the previous units. Therefore, some of the information presented in this unit will not be entirely new to you.

UNIT OBJECTIVES

When you complete this unit, you will be able to:

1. Define the following terms: Power, watt, dissipation, and horsepower.
2. State Ohm's Law.
3. Depending upon the unknown quantity, use one of the three power equations to determine the power dissipated in a circuit.
4. Select the proper equation and calculate the current in simple circuit in which two of the following quantities are known: voltage, resistance, power.
5. Select the proper equation and calculate the voltage in any simple circuit in which two of the following quantities are known: current, resistance, power.
6. Select the proper equation and calculate the resistance of any simple circuit in which two of the following quantities are known: voltage, current, power.
7. Select the proper equation and calculate the power dissipated in any simple circuit in which two of the following are known: voltage, current, resistance.
8. Describe how a voltmeter can be used to measure current.
9. State the three equation forms of Ohm's Law.

UNIT ACTIVITY GUIDE

	Completion Time
☐ Read “Ohm’s Law.”	________
☐ Complete Programmed Review Frames 1 through 12.	________
☐ Read “Power.”	________
☐ Complete Programmed Review Frames 13 through 25.	________
☐ Perform Experiment 9.	________
☐ Perform Experiment 10.	________
☐ Perform Experiment 11.	________
☐ Perform Experiment 12.	________
☐ Study Summary.	________
☐ Complete Unit Examination.	________
☐ Check Examination Answers.	________

OHM'S LAW

Ohm's Law defines the way in which current, voltage, and resistance are related. You examined this relationship to some extent in previous units of this course. This unit examines it more closely and in a systematic way.

Determining Current

Ohm's Law states that current is *directly proportional to voltage and inversely proportional to resistance*. Figure 4-1A illustrates this point. The source of voltage is the battery. Voltage is the force which causes current to flow. Therefore, the higher the voltage, the higher the current. Conversely, the lower the voltage, the lower the current. This assumes that the resistance remains constant. However, as you have seen, resistance also determines the current. Resistance is the opposition to current flow. Assuming that the voltage is constant, the higher the resistance, the lower the current. Also, the lower the resistance, the higher the current.

This formula summarizes these facts:

$$\text{current} = \frac{\text{voltage}}{\text{resistance}}$$

Or, stated in terms of the units of current, voltage, and resistance:

$$\text{amperes} = \frac{\text{volts}}{\text{ohms}}$$

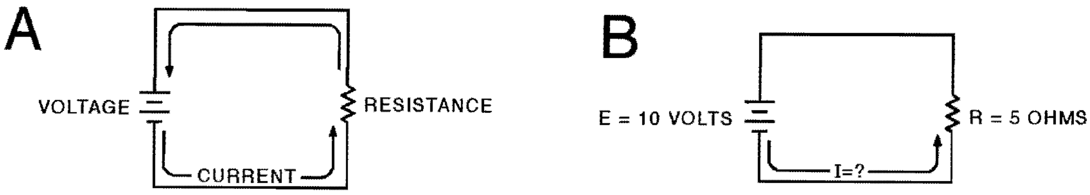


Figure 4-1
Current is determined
by voltage and resistance.

In formulas, single letters of the alphabet are used to represent current, voltage, and resistance. Resistance is represented by the letter R. Voltage may be represented either by the letter V (for voltage) or the letter E (for EMF). This course uses the letter E to represent EMF or voltage. Current is represented by the letter I. While this may seem a little illogical, this convention is used throughout electronics. If you substitute the letters I, E, and R for the quantities current, voltage, and resistance respectively; the formula for current becomes:

$$I = \frac{E}{R}$$

This formula may be used to find current in any circuit in which the voltage and resistance are known.

Figure 4-1B shows a circuit in which the values of voltage and resistance are given. To determine the current, you merely substitute the known values into the formula:

$$I = \frac{E}{R}$$

$$I = \frac{10 \text{ volts}}{5 \text{ ohms}}$$

$$I = 2 \text{ amperes}$$

Notice you simply divided 5 into 10 to obtain a final answer of 2. Anytime you divide ohms into volts, the answer is expressed in amperes. Thus, the current in the circuit shown in Figure 4-1B is 2 amperes.

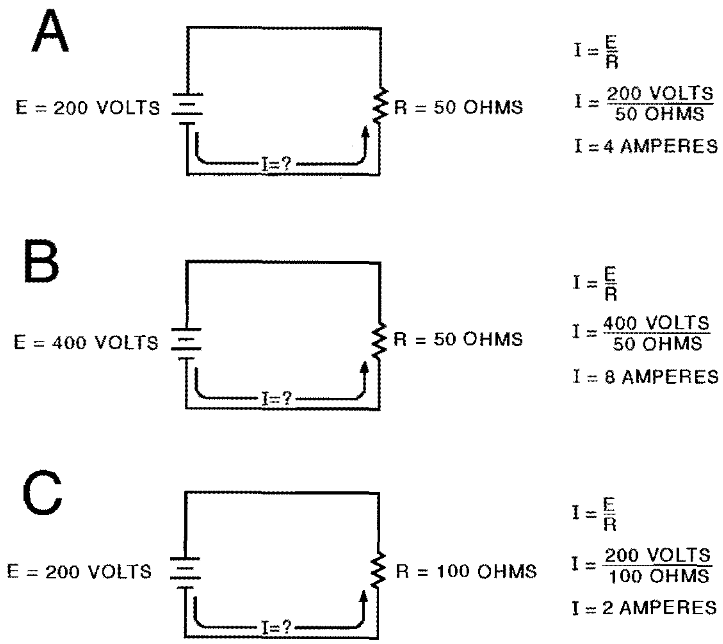

A
E = 200 VOLTS
R = 50 OHMS
I=?
I = E/R
I = 200 VOLTS / 50 OHMS
I = 4 AMPERES
B
E = 400 VOLTS
R = 50 OHMS
I=?
I = E/R
I = 400 VOLTS / 50 OHMS
I = 8 AMPERES
C
E = 200 VOLTS
R = 100 OHMS
I=?
I = E/R
I = 200 VOLTS / 100 OHMS
I = 2 AMPERES

Figure 4-2
Current is directly proportional to voltage and inversely proportional to resistance.

Figure 4-2A shows another circuit in which the value of E and R are given. When you solve for I, you find that the current is:

$$I = \frac{E}{R}$$

$$I = \frac{200 \text{ volts}}{50 \text{ ohms}}$$

$$I = 4 \text{ amperes}$$

Here's what happens to the current if you double the applied voltage as shown in Figure 4-2B.

$$I = \frac{E}{R}$$

$$I = \frac{400 \text{ volts}}{50 \text{ ohms}}$$

$$I = 8 \text{ amperes}$$

Notice that when the voltage is doubled, the current also doubles. You expect this because current is *directly proportional* to voltage.

Now return to Figure 4-2A. What happens if you double the resistance and hold the voltage constant as shown in Figure 4-2C? The current becomes:

$$I = \frac{E}{R}$$

$$I = \frac{200 \text{ volts}}{100 \text{ ohms}}$$

$$I = 2 \text{ amperes}$$

Thus, when you double the resistance, the current is reduced to one-half of its former value. You expect this since current is *inversely proportional* to resistance.

Now consider another example. How much current flows through a 3 k ohm resistor when it is connected across a 9 volt battery? The easiest way to solve this problem is to convert 3 k ohms to 3000 ohms. Thus:

$$I = \frac{E}{R}$$

$$I = \frac{9 \text{ volts}}{3000 \text{ ohms}}$$

$$I = 0.003 \text{ amperes}$$

Recall that 0.003 amperes is another way of saying 3 milliamperes. Because resistance values are often given in kilohms, it is convenient to be able to work problems without converting kilohms to ohms. In current problems, when volts are divided by kilohms, the result is expressed in milliamperes.

For example, how much current flows when a lamp with a resistance of 2.4 kilohms is connected across a 120 volt line? The current in milliamperes is:

$$I = \frac{E}{R}$$

$$I = \frac{120 \text{ volts}}{2.4 \text{ k ohms}}$$

$$I = 50 \text{ milliamperes}$$

To check this, convert 2.4 kilohms to 2400 ohms and solve as you did earlier:

$$I = \frac{E}{R}$$

$$I = \frac{120 \text{ volts}}{2400 \text{ ohms}}$$

$$I = 0.05 \text{ amperes}$$

Recall that 0.05 amperes is the same as 50 milliamperes.

Resistance is often given in megohms. For example, what is the current when a 5 megohm resistor is connected across a 25 volt battery? You can convert 5 megohms to 5,000,000 ohms and solve for current in amperes:

$$I = \frac{E}{R}$$

$$I = \frac{25 \text{ volts}}{5{,}000{,}000 \text{ ohms}}$$

$$I = 0.000\,005 \text{ amperes}$$

This is 5 microamperes. Thus, when you divide volts by megohms, the answer is in microamperes. That is:

$$I = \frac{E}{R}$$

$$I = \frac{25 \text{ volts}}{5 \text{ megohms}}$$

$$I = 5\ \mu \text{ amps.}$$

To summarize, the basic formula for current is:

$$I = \frac{E}{R}$$

If R is given in ohms, you can think of the equation as:

$$\text{amperes} = \frac{\text{volts}}{\text{ohms}}$$

However, if R is given in kilohms, you can think of the equation as:

$$\text{milliamperes} = \frac{\text{volts}}{\text{kilohms}}$$

Finally, if R is given in megohms, you can think of the equation as:

$$\text{microamperes} = \frac{\text{volts}}{\text{megohms}}$$

Finding Voltage

You saw that the formula for current is:

$$I = \frac{E}{R}$$

By *transposing* this equation, you can develop a formula for voltage. Transposing simply means changing the equation from one form to another. Since you are now interested in finding voltage, you must change the formula so that E is on one side of the equation by itself. This is easy to do if you remember a basic algebra rule for transposing equations. The rule states that you can multiply or divide both sides of the equation by any quantity without changing the equality. The current equation is:

$$I = \frac{E}{R}$$

Multiplying both sides by R you have:

$$I \times R = \frac{E \times R}{R}$$

Notice that R appears in both the numerator and the denominator of the fraction on the right side of the equation. Recall from basic mathematics that the two R's in the fraction can be cancelled like this:

$$I \times R = \frac{E \times \cancel{R}}{\cancel{R}}$$

This leaves:

$$I \times R = E$$

You can interchange the two sides of the equation without changing the equality. Interchanging the two sides, you find the basic equation for voltage:

$$E = I \times R$$

In other words, voltage is equal to current times resistance. Generally, the times sign (x) is omitted so that the formula is simply:

$$E = IR$$

Figure 4-3A shows a circuit in which the resistance and current are known. Find the voltage:

$$E = IR$$
$$E = 0.5 \text{ amperes} \times 125 \text{ ohms}$$
$$E = 62.5 \text{ volts}$$

Notice that amperes times ohms gives volts.

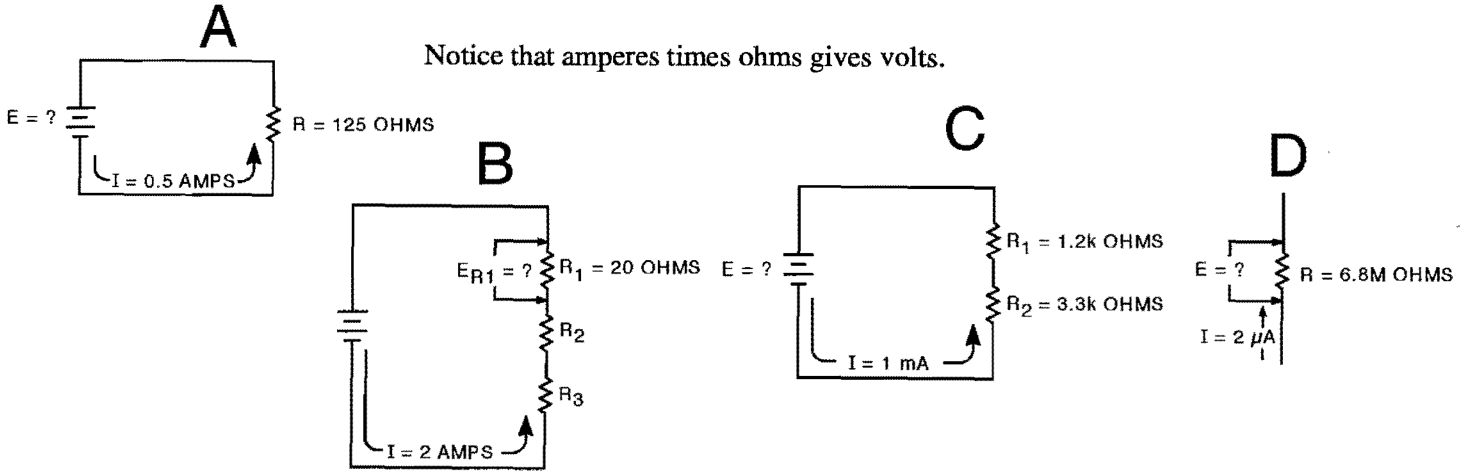


Figure 4-3
Finding voltage.

Figure 4-3B shows a slightly different problem. Here, you wish to find the voltage drop across R1. Call this voltage E_{R1}. You know that $R_1 = 20$ ohms and that the current through R_1 is 2 amperes. Consequently, you can find the voltage drop across R_1:

$$E_{R1} = I \times R_1$$
$$E_{R1} = 2 \text{ amperes} \times 20 \text{ ohms}$$
$$E_{R1} = 40 \text{ volts}$$

Figure 4-3C shows two known resistance values connected in series. The current is given, but the battery voltage is not. To find the battery voltage you must multiply the total resistance (R_T) times the current. Next, you add the two series resistances to calculate the total resistance. Thus,

$$R_T = R_1 + R_2$$
$$R_T = 1.2 \text{ k ohms} + 3.3 \text{ k ohms}$$
$$R_T = 4.5 \text{ k ohms}$$

Once you know the total resistance, you can compute the voltage. However, notice that the resistance is given in kilohms while the current is given in milliamperes. You could change kilohms to ohms and milliamperes to amperes and then solve for volts as you did above. However, this is unnecessary since milliamperes multiplied by kilohms equals volts. Thus,

$$E = I \times R_T$$
$$E = 1 \text{ milliampere} \times 4.5 \text{ kilohms}$$
$$E = 4.5 \text{ volts}$$

Figure 4-3D shows a partial schematic in which the resistance is given in megohms, the current is given in microamperes (µA), and the voltage drop is unknown. Once again, it is unnecessary to convert to ohms and amperes because megohms multiplied by microamperes gives volts. Thus, to find the voltage drop across R, you simply multiply:

$$E = I \times R$$
$$E = 2\ \mu A \times 6.8\ M\Omega$$
$$E = 13.6 \text{ volts}$$

Finding Resistance

You can transpose the current formula or the voltage formula to produce a resistance formula. For example, the voltage formula is:

$$E = IR$$

Dividing both sides by I you get:

$$\frac{E}{I} = \frac{IR}{I}$$

The I's in the fraction on the right cancel:

$$\frac{E}{I} = \frac{\cancel{I}R}{\cancel{I}}$$

So the formula becomes:

$$\frac{E}{I} = R$$

By reversing the equation, you have the formula for resistance:

$$R = \frac{E}{I}$$

This states that resistance is equal to voltage divided by current. Or,

$$\text{ohms} = \frac{\text{volts}}{\text{amperes}}$$

You can use this formula to can find the resistance in any circuit in which the voltage and current are known. Figure 4-4A shows such a circuit. Solving for R, you find that:

$$R = \frac{E}{I}$$

$$R = \frac{24\ \text{V}}{4.8\ \text{A}}$$

$$R = 5\ \text{ohms}$$

Figure 4-4B shows another example. Here, the current is given in milliamperes while the emf is expressed in volts. When milliamperes are divided into volts the result is in kilohms. Thus:

$$R = \frac{E}{I}$$

$$R = \frac{15\ \text{V}}{5\ \text{mA}}$$

$$R = 3\ \text{kilohms}$$

You can easily prove this by converting 5 mA to 0.005 A and solving for R:

$$R = \frac{E}{I}$$

$$R = \frac{15\ \text{V}}{0.005\ \text{A}}$$

$$R = 3000\ \text{ohms}$$

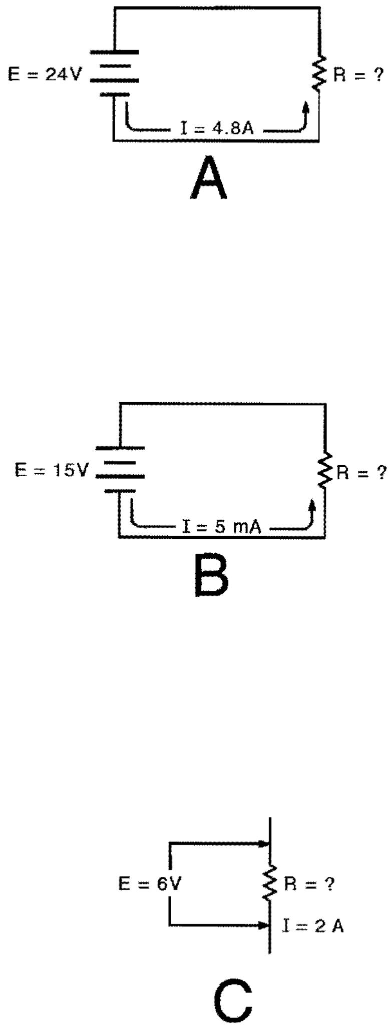


Figure 4-4
Finding resistance.

Finally, in Figure 4-4C you wish to find the resistance which drops 6 volts when the current is 2 microamps. When microamps are divided into volts the result is megohms. Thus,

$$R = \frac{E}{I}$$

$$R = \frac{6\text{ V}}{2\ \mu\text{A}}$$

$$R = 3\text{ megohms}$$

Once again you can prove this by converting 2 μA to 0.000 002 amps and dividing:

$$R = \frac{E}{I}$$

$$R = \frac{6\text{ V}}{0.000\ 002\text{ A}}$$

$$R = 3{,}000{,}000\text{ ohms}$$

Summary

Ohm's Law may be expressed by three different formulas:

$$I = \frac{E}{R}$$

$$E = IR$$

$$R = \frac{E}{I}$$

In Figure 4-5A the three quantities are diagrammed in a way that may help you to remember these three equations. To use the diagram, cover the quantity for which you wish to find the equation. For example, in Figure 4-5B you wish to find the current, so cover the quantity I. The quantity you covered is the left hand side of the equation. The remaining two symbols represent the right hand side of the equation. Notice that the remaining quantities are:

$$\frac{E}{R}$$

Therefore,

$$I = \frac{E}{R}$$

Figures 4-5C and D show how to find the formulas for resistance and voltage.

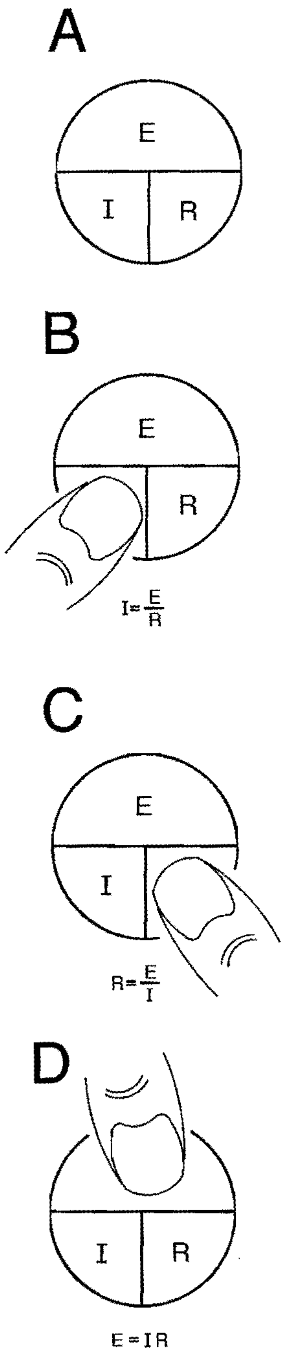


Figure 4-5
The three forms of Ohm's Law.

Some equally handy diagrams are shown in Figure 4-6. These indicate how the quantities are grouped with and without metric prefixes. In Figure 4-6A, no metric prefixes are used with any of the quantities. In any Ohm's Law problem, if two of the quantities are given in the units shown in Figure 4-6A, then the third quantity is given in the third unit. For example, if resistance is given in ohms while voltage is given in volts, then current is in amperes.

In Figure 4-6B, emf is still given in volts. However, current is given in milliamperes while resistance is given in kilohms. It is important to remember that these three quantities go together. Thus, if resistance is given in kilohms while emf is given in volts, the current is in milliamperes. Or, if current is in milliamperes while resistance is in kilohms, the emf is in volts.

Figure 4-6C shows that a similar relationship exists between volts, microamps, and megohms. For example, if emf is given in volts and current is given in microamperes, resistance is in megohms.

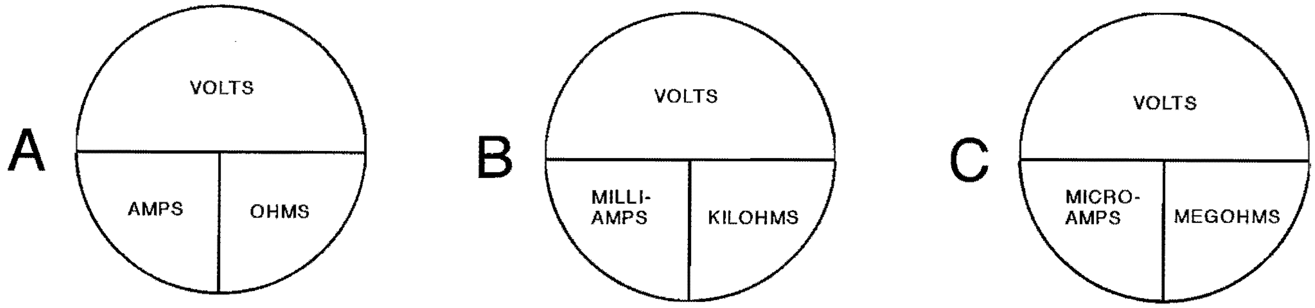


Figure 4-6
How the metric prefixes are related.

Programmed Review

1. Ohm's Law defines the relationship between the three fundamental electrical quantities: __________, __________, and __________ .

2. (current, voltage, resistance) One form of Ohm's Law states that current is equal to voltage divided by resistance. However, in equation form, symbols are normally used to represent these quantities. R represents resistance; E, voltage; and I, current. Thus, the formula for current is:

   I = __________

3. ($I = \frac{E}{R}$)

   You can use this formula to solve for current whenever voltage and resistance are known. How much current flows through a 10 ohm resistor when 5 volts are applied? __________

4. (5 volts ÷ 10 ohms = 0.5 ampere) When the emf is given in volts and resistance is given in ohms, the current is in amperes. However, if the emf is given in volts but the resistance is given in kilohms, then the current is in __________ .

5. (milliamperes) If the emf is given in volts and the resistance is given in megohms, then the current is in __________ .

6. (microamperes) Another form of Ohm's Law expresses voltage in terms of current and resistance. In equation form, it states that voltage is directly proportional to both resistance and current. This formula is E = _______.

7. (E = IR) Therefore, you can solve for voltage whenever current and resistance are known. What is the voltage drop across a 120 ohm resistor when the current through the resistor is 0.5 amperes? ____________ .

8. (.5 amperes x 120 ohms = 60 volts) The emf is in volts when current is in amperes and resistance is in ohms; when current is in milliamperes and resistance is in kilohms; and when current is in microamperes and resistance is in ____________ .

9. (megohms) The final form of Ohm's Law states that resistance is directly proportional to voltage and inversely proportional to current. As an equation, R = _________ .

10. ($R = \frac{E}{I}$)

You can use this formula to find resistance whenever voltage and current are known. What size resistor develops a voltage drop of 12 volts when a current of 0.75 amperes flows through it? ____________

11. (12 volts ÷ 0.75 amperes = 16 ohms) Resistance is in ohms when the emf is in volts and the current is in amperes. It is in kilohms when the emf is in volts and the current is in milliamperes. Finally, it is in megohms when the emf is in volts and the current is in ____________ .

12. (microamperes)

POWER

In addition to the three basic electrical quantities (current, voltage, and resistance) a fourth quantity is also very important. This quantity is called power. Power is defined as the rate at which work is done. In other words, power refers to the amount of work done in a specific length of time. Power use or loss in a circuit is called dissipation.

Work and Power

In an earlier unit you learned that a *joule* is equal to the amount of work done by one volt of emf in moving one coulomb of charge. Notice that time does not enter into this definition. Thus, the same amount of work is done whether the charge is moved in one second or in one hour.

Unlike *work*, power is concerned with time. Therefore, power is a measure of joules per unit of time. The unit of power is the *watt*. It is named in honor of James Watt who pioneered the development of the steam engine. The watt is equal to *one joule per second*. When you speak of the power used by a circuit, it is in terms of the number of watts dissipated by the circuit.

The English unit of work (the foot-pound) is easier to visualize than the joule. If one pound is lifted vertically by one foot, one foot-pound of work is done. The joule is equal to 0.738 foot-pounds. Therefore, the watt is equal to 0.738 foot-pounds per second. The unit of mechanical power in the English system is the *horsepower*. The horsepower is equal to 550 foot-pounds per second. In other words, if 550 pounds are raised one foot in one second, one horsepower is expended. In terms of watts, the horsepower is equal to 746 watts. Or, stated another way, the watt is equal to 1/746 or 0.00134 horsepower.

Power, Current, and Voltage

You have seen that a watt is equal to one joule per second. That is, a watt is the work done in one second by one volt of emf in moving one coulomb of charge. If one coulomb of charge flows in one second, the current is one ampere. Thus, one watt is the amount of power used in a circuit when one ampere of current flows as the result of one volt of applied emf.

Power is directly proportional to both current and voltage. Thus, the formula for power is:

$$\text{power} = \text{current} \times \text{voltage}$$

Or, stated in terms of the units of the three quantities:

$$\text{watts} = \text{amperes} \times \text{volts}$$

In equations, the symbol P is used to represent power. Thus, the formula for power is:

$$P = IE$$

As with Ohm's Law, there are two other useful forms of this equation. The first expresses voltage in terms of current and power. You can find it by rearranging the equation:

$$P = IE$$

Dividing both sides by I:

$$\frac{P}{I} = \frac{IE}{I}$$

Cancelling the two I's on the right side:

$$\frac{P}{I} = \frac{\cancel{I}E}{\cancel{I}}$$

Interchanging the two sides of the equation:

$$E = \frac{P}{I}$$

This states that voltage (in volts) is equal to power (in watts) divided by current (in amperes).

Another useful form of the equation is:

$$I = \frac{P}{E}$$

See if you can derive this formula from the original power formula given above.

To summarize, power, voltage, and current are related by the following formulas:

$$P = IE, \quad E = \frac{P}{I}, \quad \text{and } I = \frac{P}{E}$$

You will now use these formulas to work some sample problems.

What is the power dissipated in a circuit in which an emf of 50 volts is applied and a current of 3.2 amperes flows?

$$P = I E$$

$$P = 3.2 \text{ amperes} \times 50 \text{ volts}$$

$$P = 160 \text{ watts}$$

How much current flows through a 75 watt light bulb which is connected across a 120 volt power line?

$$I = \frac{P}{E}$$

$$I = \frac{75 \text{ watts}}{120 \text{ volts}}$$

$$I = 0.625 \text{ amperes}$$

What is the voltage drop across a light bulb that dissipates 60 watts when the current through the bulb is 0.5 amperes?

$$E = \frac{P}{I}$$

$$E = \frac{60 \text{ watts}}{0.5 \text{ amperes}}$$

$$E = 120 \text{ volts}$$

Power Dissipation in Resistors

In resistors and most other electronic components, power is dissipated in the form of heat. In some cases, the heat produced is a desired result. For example, the purpose of the resistance element in a toaster, heating pad, and electric stove is to produce heat. However, in most electronic devices, the heat produced by resistors represents wasted power.

The power lost when resistor heat up must be supplied by the power source. Since electrical power costs money, you should attempt to keep the power lost in resistors at a minimum.

Since resistors dissipate power, there must be a formula for power which involves resistance. Actually, there are two such formulas. One expresses power in terms of voltage and resistance. The other expresses power in terms of current and resistance. Here's how you derive these equations:

First, consider how P can be expressed in terms of E and R. The basic formula for power is:

$$P = I \times E \quad \textbf{or} \quad P = E \times I$$

However, from Ohm's Law you know that:

$$I = \frac{E}{R}$$

Thus, you can substitute

$$\frac{E}{R}$$

for I in the basic power equation. When you do this, the equation becomes:

$$P = E \times \frac{E}{R}$$

Or,

$$P = \frac{E^2}{R}$$

Use this formula when you wish to find the power but only the voltage and resistance are known. For example, how much power is dissipated by a 22 ohm resistor if the voltage drop across the resistor is 5 volts?

$$P = \frac{E^2}{R}$$

$$P = \frac{5^2}{22}$$

$$P = \frac{25}{22}$$

$$P = 1.136 \text{ watts}$$

How much power is delivered to a 16 ohm circuit by a 12 volt battery?

$$P = \frac{E^2}{R}$$

$$P = \frac{12^2}{16}$$

$$P = \frac{144}{16}$$

$$P = 9 \text{ watts}$$

In some cases, only the current and resistance are known. By combining the basic power formula with one of the Ohm's Law formulas, you can derive an equation in which P is expressed in terms of I and R. Recall that the basic power formula is:

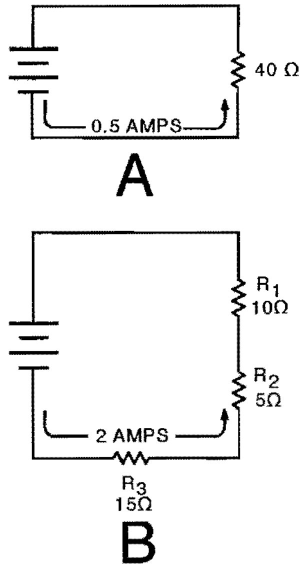


Figure 4-7
Finding the power when R and I are known.

$$P = I \times E$$

From Ohm's Law you know that E = I R. Thus, you can substitute IR for E in the power formula. The equation becomes:

$$P = I \times IR$$

$$P = I^2 R$$

Use this formula when you wish to find power but only current and resistance are known. For example, how much power is dissipated by the circuit shown in Figure 4-7A?

$$P = I^2 R$$

$$P = 0.5^2 \times 40$$

$$P = 0.25 \times 40$$

$$P = 10 \text{ watts}$$

How much power is dissipated by R_1 in Figure 4-7B?

$$P = I^2 \times R_1$$

$$P = 2^2 \times 10$$

$$P = 4 \times 10$$

$$P = 40 \text{ watts}$$

You can verify that the above equations are correct by working a sample problem three different ways. For example, consider the circuit shown in Figure 4-8. The current and voltage are given, so you can use the formula $P = I E$:

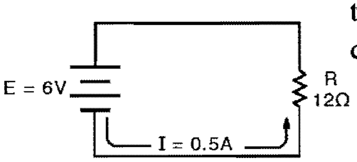


Figure 4-8
You can use any of the power formulas to find power.

$$P = I E$$

$$P = 0.5 \times 6$$

$$P = 3 \text{ watts}$$

Or, since voltage and resistance are given, you can use the formula

$$P = \frac{E^2}{R}$$

$$P = \frac{E^2}{R} = \frac{6^2}{12} = \frac{36}{12} = 3 \text{ watts}$$

Or, since current and resistance are given, you can use the formula

$$P = I^2 R$$

$$P = 0.5^2 \times 12$$

$$P = 0.25 \times 12$$

$$P = 3 \text{ watts}$$

Notice that the same result is achieved regardless of the power equation you use.

Deriving More Equations

Earlier you saw that the basic power equation ($P = IE$) can be rearranged to form current and voltage equations. Namely:

$$E = \frac{P}{I} \text{ and } I = \frac{P}{E} .$$

In much the same way, the equation:

$$P = \frac{E^2}{R}$$

can be rearranged to form an equation for voltage. That is:

$$P = \frac{E^2}{R}$$

When you multiply both sides by R, you find:

$$P \times R = \frac{E^2}{R} \times R$$

The two R's on the right cancel:

$$P \times R = \frac{E^2}{R} \times R$$

Thus,

$$P \times R = E^2$$

Now you can take the square root of both sides of the equation to get rid of the exponent:

$$\sqrt{P \times R} = \sqrt{E^2}$$

Or:

$$\sqrt{P \times R} = E$$

Notice that this equation expresses voltage in terms of power and resistance.

This equation allows you to work problems like the one shown in Figure 4-9. Here, the resistance and power are given but the voltage is unknown:

$$E = \sqrt{PR}$$

$$E = \sqrt{3 \times 1200}$$

$$E = \sqrt{3600}$$

$$E = 60 \text{ volts}$$

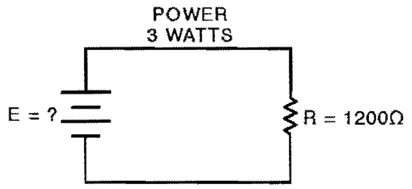


Figure 4-9

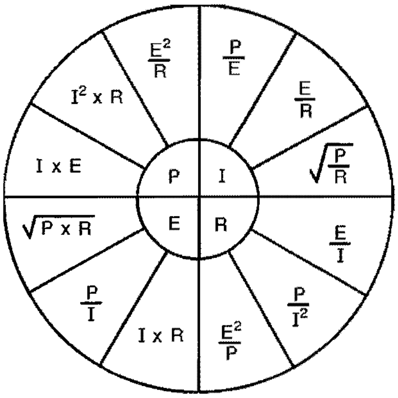
Finding voltage when resistance and power are known.

In the same way, the equation $P = I^2 R$ can be converted to a current equation. That is:

$$P = I^2 R$$

Divide both sides by R and let the R's on the right side cancel:

$$\frac{P}{R} = \frac{I^2 R}{R}$$



$\frac{E^2}{R}$
$\frac{P}{E}$
$I^2 \times R$
$\frac{E}{R}$
$I \times E$
P
I
$\sqrt{\frac{P}{R}}$
$\sqrt{P \times R}$
E
R
$\frac{E}{I}$
$\frac{P}{I}$
$\frac{P}{I^2}$
$I \times R$
$\frac{E^2}{P}$

Figure 4-10
Wheel diagram for finding the proper equation for current, voltage, resistance, and power.

This leaves:

$$\frac{P}{R} = I^2$$

Take the square root of both sides:

$$\sqrt{\frac{P}{R}} = I$$

Thus, current can be expressed in terms of power and resistance.

By rearranging the equations:

$$P = I^2 R$$

and

$$P = \frac{E^2}{R}$$

you can obtain equations for R. The derivation is not shown, but the final equations are:

$$R = \frac{P}{I^2} \text{ and } R = \frac{E^2}{P}$$

In this unit, you learned twelve important formulas. Figure 4-10 is a wheel diagram which may help you remember these equations. The inner circle contains the four basic units: power, current, voltage, and resistance. The outer circle contains three formulas for each quantity. For example, the three formulas for resistance are:

$$R = \frac{E}{I}, R = \frac{E^2}{P}, \text{ and } R = \frac{P}{I^2}$$

You can use this diagram to quickly find the proper formula for any problem in which two of the quantities are known.

While it is not necessary to memorize these 12 equations, you should memorize the basic Ohm's Law and power formulas as soon as possible. That is, you should memorize these two equations:

$$E = IR \text{ and } P = IE$$

If you know these two formulas, you can derive any of the other formulas with some mathematical manipulations as you have seen. Until you become more familiar with these equations, use the diagram shown in Figure 4-10 as an aid.

Programmed Review

13. In addition to current, voltage, and resistance, a fourth important electrical quantity is ___________ .

14. (power) Power refers to the amount of work done in a specific length of time. The unit of work is the joule and the unit of time is the second. Thus, power is a measure of ___________ per second.

15. (joules) The unit of power is the watt. It is equal to one ___________ per second.

16. (joule) The unit of mechanical power is the horsepower. You can compare electrical power to horsepower since one horsepower is equal to 746 watts. Thus, one watt is equal to 1/746 horsepower or, expressed as a decimal fraction ___________ horsepower.

17. (0.00134) Power (P) is directly proportional to both current (I) and voltage (E). Thus, the formula for power is: P = ___________ .

18. ($P = I \times E$) How much power is dissipated by a resistor which drops 3.2 volts when a current of 0.75 amperes flows through it? ___________ watts.

19. (2.4 watts) The basic power formula ($P = I \times E$) can be rearranged so that current is expressed in terms of power and voltage. In this form the equation becomes I = ________ .

20. ($I = \frac{P}{E}$)

Also, it can be rearranged so that E is expressed in terms of I and P. The formula is E = ____________ .

21. ($E = \frac{P}{I}$)

The power formula can be combined with the three Ohm's Law formulas to produce several new equations. These equations are summarized in Figure 4-10. It is important that you are able to pick the correct formula from those diagrammed in Figure 4-10. For example, in a problem in which I and R are known but P is unknown, the proper equation for finding P is P = ____________ .

22. ($P = I^2 \times R$) As another example, if you know power and voltage, the formula for finding resistance is R = ____________ .

23. ($R = \frac{E^2}{P}$)

Use this formula to find the resistance of the heating element in a 1000-watt, 120-volt toaster? ____________ .

24. (14.4 ohms) Now that you know the power, voltage, and resistance, you can use any of the I formulas to find the current through the toaster. The current is ____________ amperes.

25. (8.333)

EXPERIMENT 9

Measuring Current

OBJECTIVES: *To demonstrate that a voltmeter and a known resistor can be used as an ammeter to determine current* flow.

To demonstrate the characteristics of an ammeter.

Introduction

To verify Ohm's Law by experimentation, you must be able to measure current, voltage, and resistance. Many general purpose meters have the capability to measure these three electrical quantities directly. On the other hand, there are some perfectly good meters which do not have current scales. The reason for this is that the ammeter function simply is not as handy as the voltmeter and ohmmeter functions.

Fortunately, a simple technique allows you to use any voltmeter as an ammeter. Recall that the voltage dropped by a resistor is directly proportional to the current through the resistor. For example, a drop of 1 volt across a 1000 ohm resistor means that a current of 1 milliamp flows through the resistor. That is:

$$I = \frac{E}{R}$$

$$I = \frac{1\ \text{V}}{1000\ \Omega}$$

$$I = 0.001\ \text{A or } 1\ \text{mA}$$

A drop of 10 volts across the same resistor means that a current of 10 milliamperes flows since:

$$I = \frac{E}{R}$$

$$I = \frac{10\ \text{V}}{1000\ \Omega}$$

$$I = 0.01\ \text{A or } 10\ \text{mA}$$

Therefore, the 1-volt scale on your voltmeter becomes a 1-milliampere scale when you connect the voltmeter across a 1000 ohm resistor. Also, the 10-volt scale becomes a 10 milliampere scale. A 2.5-volt scale becomes a 2.5-milliampere scale, etc. The reason for this is that each milliamp of current through the 1000 ohm resistor causes a voltage drop of one volt.

Material Required

Heathkit Analog Trainer

Voltmeter (multimeter) with test leads

1 — 1000 Ω, 1%, 1/2-watt resistor (brown-black-black-brown-brown)
1 — 100 Ω, 1%, 1/2-watt resistor (brown-black-black-black-brown)
1 — 1200 Ω, 5%, 1/2-watt resistor (brown-red-red-gold)
1 — 22 kΩ, 5%, 1/2-watt resistor (red-red-orange-gold)
#22 copper wire

Procedure

1. Construct the circuit shown in Figure 4-11 on the left side of your Trainer breadboard.

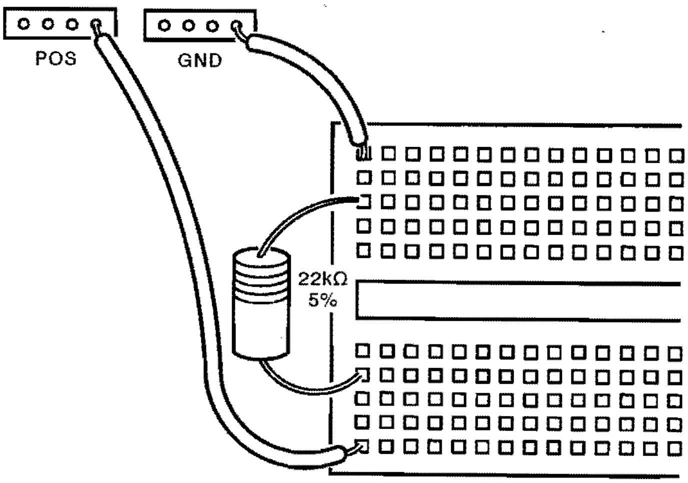


Figure 4-11
Circuit for Experiment 9.

2. With the meter set to measure voltage, connect the voltmeter from the POS to the GND terminal. Switch the Trainer ON and adjust the + voltage control for an indication of +11 volts. Disconnect the voltmeter.

3. The circuit is now set up as shown in Figure 4-12A. Use the values given to compute the current through the resistor. The computed current is ____________ milliamperes.

4. If your meter has an ammeter scale, break the circuit (after you turn the Trainer off) and insert the ammeter as shown in Figure 4-12B. The measured current is ____________ milliamperes. Is the measured current approximately the same as that computed in Step 3? ____________ .

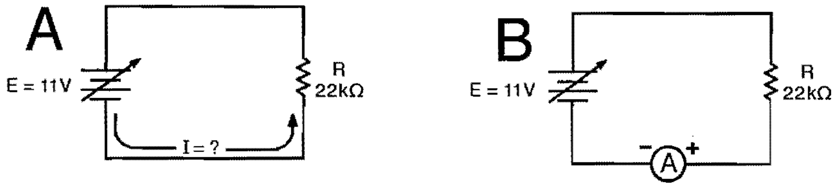

A
E = 11V
R
22kΩ
I = ?
B
E = 11V
R
22kΩ
A

Figure 4-12

Determine the current through the resistor.

5. Whether or not your meter has an ammeter scale, it is convenient to know how to convert a voltmeter to an ammeter. Leave the circuit shown in Figure 4-11 connected. At the right side of the breadboard area on the Trainer, construct the circuit shown in Figures 4-13A and 4-13B.

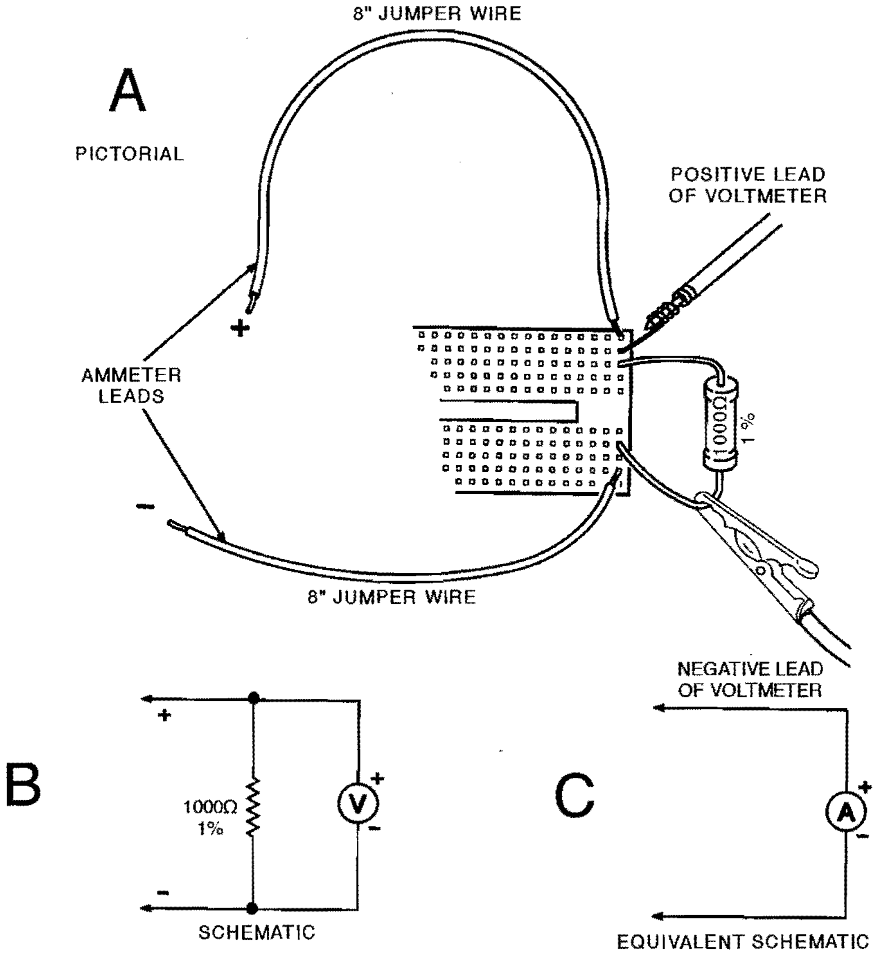
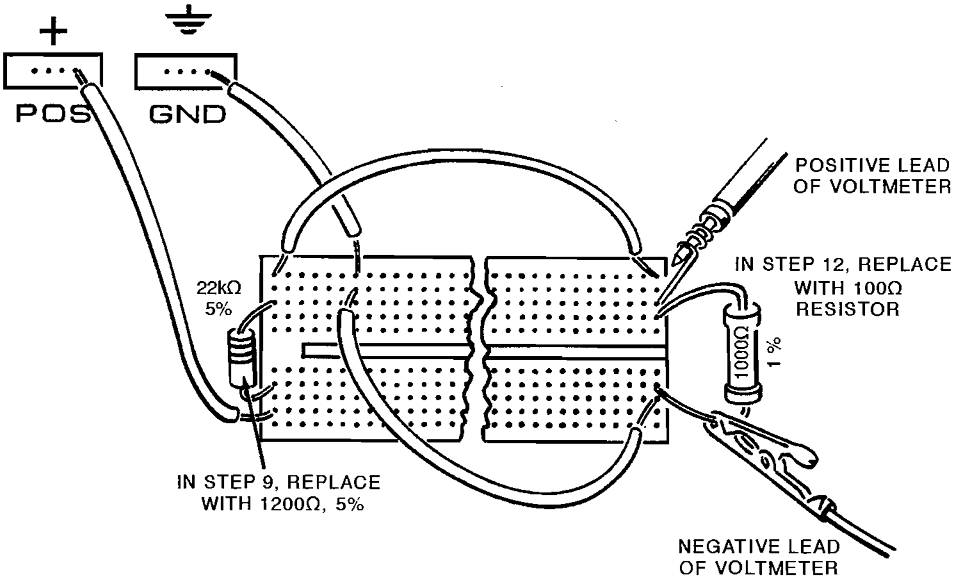

8" JUMPER WIRE
A
PICTORIAL
POSITIVE LEAD OF VOLTMETER
+
AMMETER LEADS
1000Ω
1%
-
8" JUMPER WIRE
NEGATIVE LEAD OF VOLTMETER
B
+
1000Ω
1%
V
-
SCHEMATIC
C
A
EQUIVALENT SCHEMATIC

Figure 4-13

Converting the voltmeter to an ammeter.

6. Set the voltmeter to the 1 VDC scale. (If your meter does not have a 1 VDC scale, use the next closest scale above 1 VDC, for example, 2.5 VDC. The meter and the 1000 ohm, 1 percent resistor are now connected as a milliammeter, as shown in the equivalent schematic in Figure 4-13C. The meter indicates milliamperes rather than volts. For example, the 1-volt point on the scale now indicates 1 milliampere. The leads for the ammeter are the free ends of the two 8" jumper wires.

7. Break the circuit on the left side of the breadboard and insert the newly constructed ammeter as shown in Figure 4-14. The measured current is ____________ milliamperes. Is the measured current approximately the same as the current computed in Step 3? ____________ .



+
POS
GND
22kΩ
5%
POSITIVE LEAD
OF VOLTMETER
IN STEP 12, REPLACE
WITH 100Ω
RESISTOR
1000Ω
1%
IN STEP 9, REPLACE
WITH 1200Ω, 5%
NEGATIVE LEAD
OF VOLTMETER

Figure 4-14
Insert the ammeter into the circuit.

Discussion

The voltage is 11 volts while the resistance is 22 kilohms. Thus, the current computed in Step 3 is:

$$I = \frac{E}{R}$$

$$I = \frac{11\ \text{V}}{22\ \text{k}\Omega}$$

$$I = 0.5\ \text{mA}$$

The current you measured in Steps 4 and 7 should both be approximately 0.5 mA. If your meter has an ammeter scale, the current you measured in Step 4 is probably slightly more accurate than that obtained in Step 7. The reason for this becomes obvious if you compare Figure 4-15A with Figure 4-15B. In Figure 4-15A, an actual ammeter is used. Such a meter generally has a very low resistance. Thus, the resistance of the meter does not significantly change the total resistance of the circuit. However, look at the situation shown in Figure 4-15B. Here, the resistor across which the voltmeter is connected adds 1000 ohms to the total resistance of the circuit. Thus, the total resistance becomes 22 kilohms plus 1 kilohm or 23 kilohms. This changes the current to:

$$I = \frac{E}{R}$$

$$I = \frac{11\ \text{V}}{23\ \text{k}\Omega}$$

$$I = 0.478\ \text{mA}$$

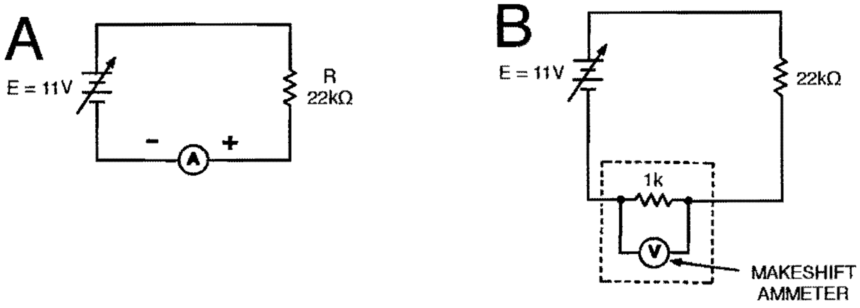


Figure 4-15
The ammeter adds resistance to the circuit which decreases the current.

This illustrates that when you measure the current, the current changes slightly. The error will be slight as long as the total resistance of the circuit is quite large compared to the resistance of the ammeter. However, if the resistance of the meter is a significant portion of the total resistance in the circuit, the error becomes quite large. The next part of this experiment proves this.

Procedure (Continued)

8. Restore the circuit on the left side of the breadboard area to the condition shown in Figure 4-11.

9. Replace the 22 k ohm resistor with the 1200 ohm 5 percent resistor. Calculate the current in the circuit. The calculated current is ____________ milliamperes.

10. Because the current is greater than 1 milliampere, you must switch your makeshift ammeter to a higher range. To do this, switch the voltmeter to the 10 VDC scale. The voltmeter and resistor combination now indicate ____________ milliamperes for a full-scale deflection.

11. As you did in Figure 4-14, insert the makeshift ammeter in series with the 1200 ohm resistor and measure the current. The measured current is ____________ milliamperes. Does this reading agree with the computed current in Step 9? ____________ . If not, how do you account for the error?

12. Replace the 1000 ohm 1 percent resistor with the 100 ohm 1 percent resistor. With the voltmeter connected across the 100 ohm resistor, each volt must be caused by ____________ milliamperes of current through the 100 ohm resistor.

13. Switch the voltmeter back to the 1 volt range. Here, a 1 volt reading indicates ____________ milliamperes of current. Thus, the current in the circuit is now ____________ milliamperes. Is this measured current approximately the same as the current you computed in Step 9? ____________ . Which resistor (the 1000 ohm or the 100 ohm) allowed you to obtain the most accurate current reading? ____________ . Why? ____
____
____ .

14. Switch the Trainer OFF.

Discussion

The current you calculated in Step 9 is:

$$I = \frac{E}{R}$$

$$I = \frac{11\text{ V}}{1200\ \Omega}$$

$$I = 9.166\text{ mA}$$

When you switch the voltmeter to the 10V range, this allows the meter and resistor to indicate currents as high as 10 mA. However, in Step 11 when the ammeter is placed in series with the 1200 ohm resistor, you find that the current is only about one-half of the computed value. The reason for this is that the makeshift ammeter adds 1000 ohms to the circuit resistance. Thus, the resistance becomes 1200 ohms plus 1000 ohms or 2200 ohms. This reduces the current to:

$$I = \frac{E}{R}$$

$$I = \frac{11\ \text{V}}{2200\ \Omega}$$

$$I = 5\ \text{mA}$$

The resistance which the ammeter adds to the circuit causes a great error in the reading.

You can reduce this error by reducing the resistance of the ammeter. In Step 12, the 1000 ohm resistor was replaced by a 100 ohm resistor. This changes the reading of the makeshift ammeter since 10 milliamps of current is required in a 100 ohm resistor to produce 1 volt. In Step 13, you measured the current with the 100 ohm ammeter. This time the measured current was much closer to the current which you computed in Step 9. The reason is that this new ammeter adds only 100 ohms of resistance to the circuit. Thus, the total circuit resistance becomes 1200 ohms plus 100 ohms or 1300 ohms. The current is now:

$$I = \frac{E}{R}$$

$$I = \frac{11\ \text{V}}{1300\ \Omega}$$

$$I = 8.46\ \text{mA}$$

Notice that an error still exists, but the error with the 100 ohm ammeter is significantly less than that caused by the 1000 ohm ammeter. In practice, the lower the resistance of the ammeter, the lower the error. The ideal ammeter would have a resistance of 0. Such a meter would introduce no error at all.

In this experiment you learned how to convert a voltmeter to a crude ammeter. You also gained some experience measuring voltage and current. Finally, you saw that measuring a current, changes the current. This is especially true if the ammeter has a high resistance.

EXPERIMENT 10

Verifying Ohm's Law

OBJECTIVE: *To verify Ohm's Law.*

Introduction

Ohm's Law states that the current in a circuit is directly proportional to the applied voltage, and inversely proportional to the circuit resistance. There are three forms of Ohm's Law expressed as three formulas:

$$I = \frac{E}{R};\ E = IR;\ \text{and } R = \frac{E}{I}$$

You can verify these formulas by experimentation.

Material Required

1 — Heathkit Analog Trainer
1 — Multimeter with test leads
1 — 33 kΩ, 5%, 1/2-watt resistor (orange-orange-orange-gold)
1 — 1000 Ω, 1%, 1/2-watt resistor (brown-black-black-brown-brown)
1 — 2000 Ω, 5%, 1/2-watt resistor (red-black-red-gold)
1 — 100 Ω, 1%, 1/2-watt resistor (brown-black-black-black-brown)
2 — 1000 Ω, 5%, 1/2-watt resistor (brown-black-red-gold)
2 — 10 kΩ, 5%, 1/2-watt resistor (brown-black-orange-gold)
#22 copper wire

Procedure

1. Use your ohmmeter to measure the resistance of the 33 kilohm, 5 percent resistor. The measured resistance is ____________ kilohms. Is this value within the 5 percent tolerance? ____________ .

2. Connect your voltmeter between GND and the POS terminals on the Trainer. Switch the Trainer ON and adjust the + voltage control until the meter reads +14 volts.

3. According to Ohm's Law, how much current should flow if the resistor value you measured in Step 1 is connected across the voltage set in Step 2? ____________ mA.

4. Switch the Trainer off and connect the circuit shown in Figure 4-16. Switch the Trainer on and measure the current in the circuit. The current is ____________ milliamperes.

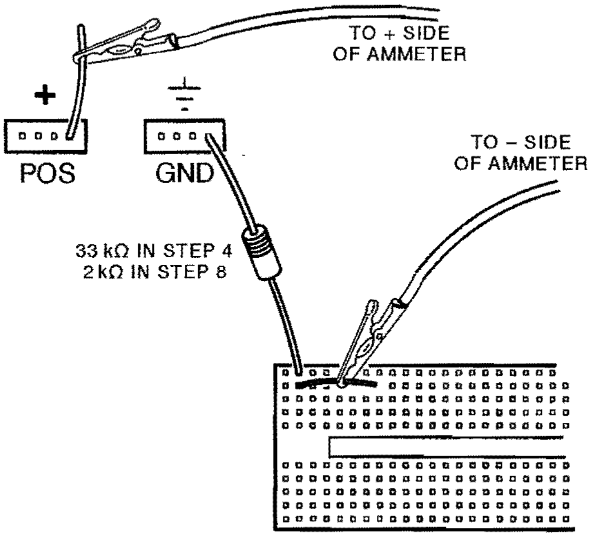

TO + SIDE OF AMMETER
+
POS
GND
TO – SIDE OF AMMETER
33 kΩ IN STEP 4
2 kΩ IN STEP 8

Figure 4-16

Circuit for Steps 4 and 8 of Experiment 10.

5. If your meter does not have a current function, you will have to convert your voltmeter to a makeshift ammeter by using the technique discussed in the previous experiment. Construct the circuit shown in Figure 4-17. Notice that the voltmeter in parallel with the 1000 ohm, 1 percent resistor forms the makeshift ammeter. Recall that this arrangement converts the 0-1 volt scale to a 0-1 milliampere scale. Using this makeshift ammeter, measure the current in the circuit. The current is ___________ milliamperes.

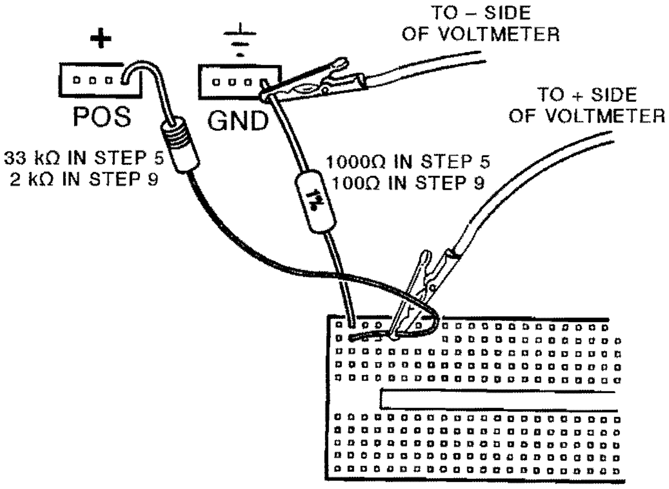

TO – SIDE OF VOLTMETER
+
POS
GND
TO + SIDE OF VOLTMETER
33 kΩ IN STEP 5
2 kΩ IN STEP 9
1000Ω IN STEP 5
100Ω IN STEP 9
1%

Figure 4-17

Circuit for Steps 5 an 9 of Experiment 10.

6. Does the value of current measured in Step 4 (or Step 5) agree with the value you computed in Step 3? ____________ .

7. Use the ohmmeter to measure the resistance of the 2000 ohm, 5 percent resistor. The measured resistance is ____________ ohms. Is this within tolerance? ____________ .

8. If your meter has current scales, use the 2000 ohm resistor to construct the circuit shown in Figure 4-16.

9. If your meter does not have current scales, use the 100 ohm 1 percent resistor in conjunction with your voltmeter and construct the circuit shown in Figure 4-17. The 100 ohm resistor and the voltmeter are now connected as a makeshift ammeter. Read the 0-1 volt scale as 0-10 milliamperes.

10. Adjust the + voltage control until the current through the circuit is 6 milliamperes.

11. Use the value of resistance you measured in Step 7 and the value of current you set in Step 10 to compute the value of voltage that is being applied to the circuit. The computed voltage is ____________ volts.

12. Do not touch the + voltage control while connect the voltmeter from the POS terminal to the GND terminal on the Trainer. The measured voltage is ____________ volts. Does this voltage agree with the value you computed in Step 11? ____________ .

13. Locate the 100 kilohm potentiometer on your Trainer. Use your ohmmeter to measure the resistance of the pot. To do this, connect one test lead to the *middle* (wiper), and the other to either of the outer terminals of the pot. Now, adjust the resistance of the pot to *maximum* resistance, that is, 100 kilohm. Carefully, note which two terminals you are measuring this maximum resistance between—you will need to use these *same* two terminals in Step 15.

14. With the + voltage control on your Trainer set to *minimum* voltage (ccw), adjust your meter to read DC volts at 12 volts or greater, and connect the + lead of your voltmeter directly to the +POS terminal of the Trainer. Connect the negative (common) lead of your voltmeter to the GND terminal. As you watch the display of your voltmeter, gradually increase the voltage of the +POS voltage control until your meter indicates exactly +12 VDC.

15. **If your meter has no current scales, go to Step 16.** If your meter has current scales, connect the circuit shown in Figure 4-18. With the 100 kilohm pot still set to maximum resistance (as in Step 13), connect the +POS voltage terminal to the same outer pot terminal that you used in Step 13.

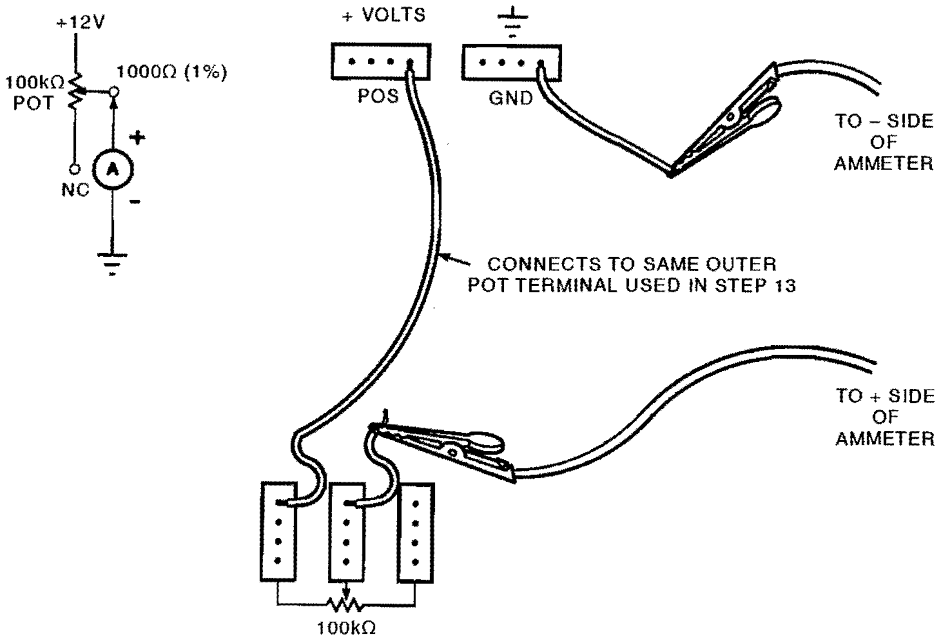

+12V
100kΩ POT
1000Ω (1%)
+
A
NC
-
+ VOLTS
POS
GND
TO - SIDE OF AMMETER
CONNECTS TO SAME OUTER POT TERMINAL USED IN STEP 13
TO + SIDE OF AMMETER
100kΩ

Figure 4-18

Schematic and wiring diagram for Step 15 of Experiment 10.

16. If your meter does not have current scales, construct the circuit shown in Figure 4-19. Here, the 1000 ohm, 1 percent resistor and the voltmeter form a makeshift ammeter. Remember to read the 0-1 volt scale as a 0-1 mA scale (read the 2.5 V scale as a 2.5 mA scale, etc.).

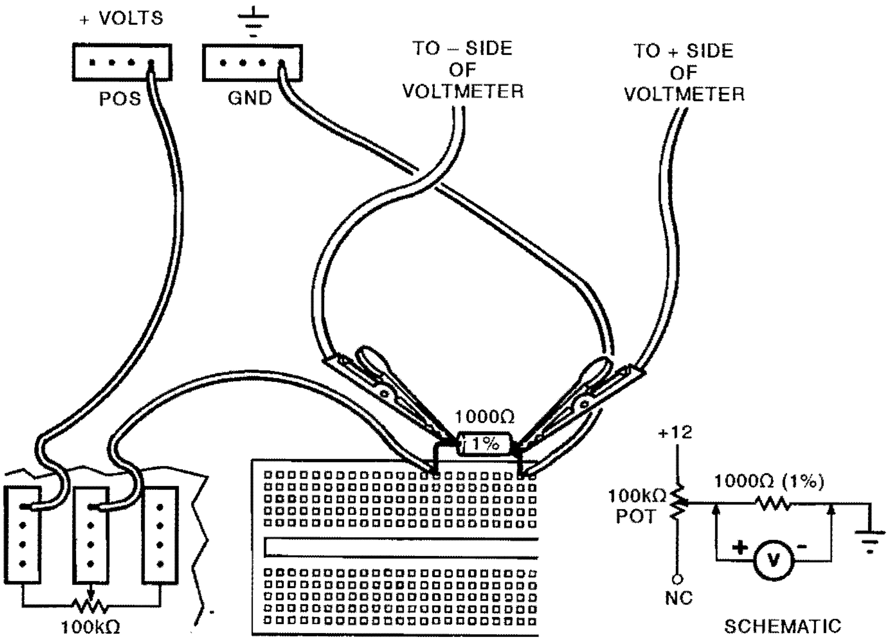


Figure 4-19

Schematic and wiring diagram for Step 15 of Experiment 10.

17. Carefully watch the response of your meter while you slowly adjust the 100 kilohm potentiometer ccw until the ammeter reads exactly 0.5 milliamperes. Be very careful not to increase the current too fast, meter damage could result.

18. Use the value of the voltage you set in Step 14 and the value of current you set in Step 17 to compute the value to which the potentiometer is presently set. The resistance is ____________ kilohms.

19. Do not touch the shaft setting, while you switch the Trainer off and disconnect the wires and leads from the 100 kilohm potentiometer.

20. Use the ohmmeter to measure the resistance between the terminals you used earlier on the 100 kilohm potentiometer. The measured resistance is ____________ kilohms. Does this reading agree approximately with the value you computed in Step 18? ___________

Discussion

In Steps 1 through 6, you verified Ohm's Law by proving that the actual current flowing through a circuit agrees with the value you computed with the current equation of Ohm's Law. The resistance value you measured in Step 1 should be approximately 33 kilohms. In Step 2, you set the voltage across this resistor to 14 volts. In Step 3, you computed the current:

$$I = \frac{E}{R} = \frac{14\text{ V}}{33\text{ k}\Omega} = 0.4242\text{ mA}$$

Your computed value may vary from this value, since you used the measured value of the resistor. In Step 4 (or Step 5) you measured the current. Your measured value should be within about 10 percent of the computed value.

In Steps 7 through 12, you verified Ohm's Law in a different way. Here, you measured the resistance (2000 ohms), set the current (6 milliamperes), and computed the voltage (12 volts). You then measured the voltage and verified that it was very close to the computed value.

In Steps 13 through 19, you verified Ohm's Law in still another way. Here, you set the voltage to 12 volts, set the current to 0.5 mA, and then computed the value of the resistance:

$$R = \frac{E}{I} = \frac{12\text{ volts}}{0.5\text{ mA}} = 24\text{ k}\Omega$$

Finally, you measured the value of the resistance to verify that the measured value was the same as the computed value.

In many cases, the computed value will not agree *exactly* with the measured value. However, this is not a flaw in Ohm's Law. Instead, the minor errors are introduced by meter tolerances, difficulties reading the meter scales exactly, errors introduced by the makeshift ammeter, etc.

Procedure (Continued)

21. Construct the circuit shown in Figure 4-20A on your Trainer. Figure 4-20B shows how the circuit could be connected.

22. Connect your voltmeter between the GND terminal and the POS terminal on the Trainer. Switch the Trainer on and adjust the + voltage to exactly +10 volts.

23. Now, break the circuit and connect your ammeter to the circuit at point C in Figure 4-20B. Be sure to observe the correct polarity when you connect the ammeter into the circuit. The total current through the current is ____________ milliamperes. Disconnect the ammeter and reconnect the circuit.

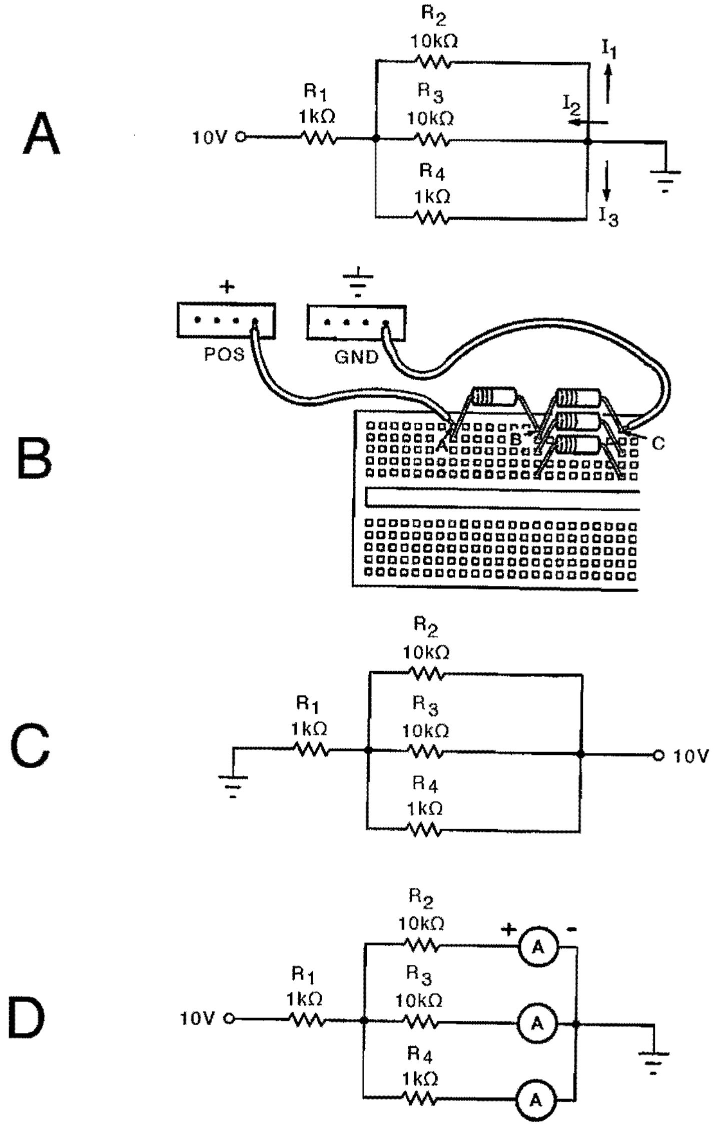

A
R2
10kΩ
R1
1kΩ
R3
10kΩ
R4
1kΩ
10V
I1
I2
I3
B
+
POS
GND
A
B
C
C
R2
10kΩ
R1
1kΩ
R3
10kΩ
R4
1kΩ
10V
D
R2
10kΩ
+
-
A
R1
1kΩ
R3
10kΩ
A
10V
R4
1kΩ
A

Figure 4-20
Circuit and schematic wiring diagrams for
Steps 21, 23, 26, 27, 29, and 30 of Experiment 10.

24. Now, use the voltage applied to the circuit, the total current through the circuit, and Ohm's Law to calculate the total resistance of the circuit. The total resistance is ____________ ohms.

25. Use the equations for resistance from Unit 3 to calculate the resistance of the complete circuit. This resistance is ____________ ohms. Is there any difference between the total resistance you calculated in Step 24 and the total resistance you calculated in Step 25? ____________. If so, why? ____________
____

26. Use the nominal value of series resistor R_1, 1000 ohms, and the current you measured in Step 23 to calculate the voltage dropped across resistor R_1. The voltage is ____________ volts. Reconfigure the test circuit like the one shown in Figure 4-20C. To do this, interchange the leads from the dc power supply. With your voltmeter, measure the voltage across R_1. The actual voltage is ____________ volts.

27. Now return the circuit to its original configuration as shown in Figure 4-20A. Measure the voltage drop across the parallel network which consists of resistors R_2, R_3, and R_4. Because the resistors are connected in parallel, you can measure the voltage across any parallel resistor. The voltage drop across the network is ____________ volts.

28. Use the voltage drop you measured across the parallel network and the nominal value of resistors R_2, R_3, and R_4 to determine the current through each of the resistors. The current through R_2 is ____________ milliamperes, the current through R_3 is ____________ milliamperes, and the current through R_4 is ____________ milliamperes. Is the total current you measured in Step 23 approximately the same as the sum of the three calculated currents? ________

29. Now disconnect resistor R_2 at point C shown in Figure 4-20B. Connect your ammeter in series with the disconnected end of R_2 and point C. Measure the current through R_2. The current through R_2 is ____________ milliamperes. Now reconnect R_2 to the circuit.

30. Repeat Step 29 with resistors R_3 and R_4. The current through R_3 is ____________ milliamperes and the current through R_4 is ____________ milliamperes. The current measurements you made in Steps 29 and 30 are shown schematically in Figure 4-20D.

31. Switch the Trainer OFF.

Discussion

In Step 23 of this section, you measured the total current through the series-parallel circuit. In Step 24, you used Ohm's Law to determine the resistance of the circuit. Then, in Step 25, you used the resistance formulas from Unit 3 to calculate circuit resistance. This resistance is:

$$R = \frac{E}{I} = \frac{10 \text{ volts}}{5.45 \text{ mA}} = 1833.3\ \Omega$$

The resistance that you calculated with Ohm's Law was, more than likely, not the same as the resistance that you calculated with the resistance equations from Unit 3. The actual resistance in the circuit is the Ohm's Law resistance. The resistance you determined with the resistance equations is based upon the nominal value of the resistors. However, because the actual value of the resistors can vary as much as ±5%, the total resistance of the circuit may also vary as much as ±5%.

In Step 26, you used the total circuit current and the nominal value of resistor R_1 to determine the voltage drop across R_1. Again, this value may vary from the actual measured voltage drop by as much as ±5%. However, your calculated and measured voltages should both be approximately 5.45 V.

In Step 27, you measured the voltage across the parallel network. You then used Ohm's Law, this measured voltage, and the nominal value of the resistors to determine the current through resistors R_2, R_3, and R_4. The current through R_2 was approximately 0.455 mA, the current through R_3 was about 0.455 mA and the current through R_4 was approximately 4.55 mA. The actual measured currents, you determined in steps 29 and 30, varied somewhat from these figures.

As you can see from this experiment, Ohm's Law can be used to determine the current, voltage, and resistance in the entire circuit or in any component of the circuit. All that is required is that you know two of the three values.

It is also apparent that, in order to achieve the greatest accuracy, you should use actual measured values for the calculations. In many instances, however, this is not necessary or practical and you can use nominal values.

EXPERIMENT 11

Power

OBJECTIVES: *To verify the three power equations.*

To demonstrate that power is dissipated in the form of heat in resistors.

To demonstrate the importance of the power rating of resistors.

Introduction

There are three commonly used equations to determine the power in a circuit. These are:

$$P = EI\,;\, P = \frac{E^2}{R}\,;\text{ and } P = I^2R\,.$$

These allow you to compute power when you know any two of the three quantities voltage, current, and resistance. Unless you have a special instrument called a wattmeter, you cannot measure power directly. However, you can measure voltage, current, and resistance, and then use the above equations to compute the power.

Material Required

1 — Heathkit Analog Trainer
1 — Multimeter with test leads
1 — 100 Ω, 5% 2-watt resistor (brown-black-brown-gold)
1 — 100 Ω, 5%, 1/2-watt resistor (brown-black-brown-gold)
1 — 10 Ω, 1%, 1/2-watt resistor (brown-black-black-gold-brown)
Soldering iron and solder
#22 copper (hook-up) wire

Procedure

1. Measure the value of the 100 ohm, 2-watt resistor. The value is ____________ ohms.

2. Connect your voltmeter between the GND and POS terminals on the Trainer, switch the Trainer on, and adjust the + voltage control until the meter indicates +10 volts.

3. If your meter has current scales, connect the circuit shown in Figure 4-21 and measure the current. The current is ____________ mA.

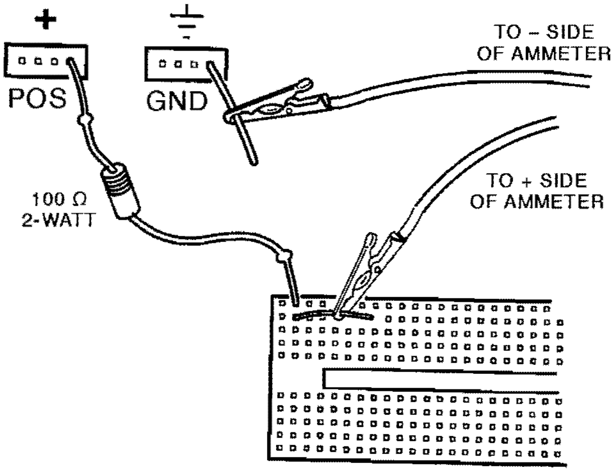

+
POS
GND
TO – SIDE
OF AMMETER
TO + SIDE
OF AMMETER
100 Ω
2-WATT

Figure 4-21
Resistor and circuit for Step 3 of Experiment 11.

4. If your meter does not have current scales, connect the circuit shown in Figure 4-22. The 10 ohm resistor and the voltmeter form a makeshift ammeter. Each volt that develops across the 10 ohm resistor represents a current of __________ mA. Therefore, you read the 0-1 V scale on the meter as a 0-__________ mA scale. Use this makeshift ammeter to measure the current in the circuit. The current is __________ mA.

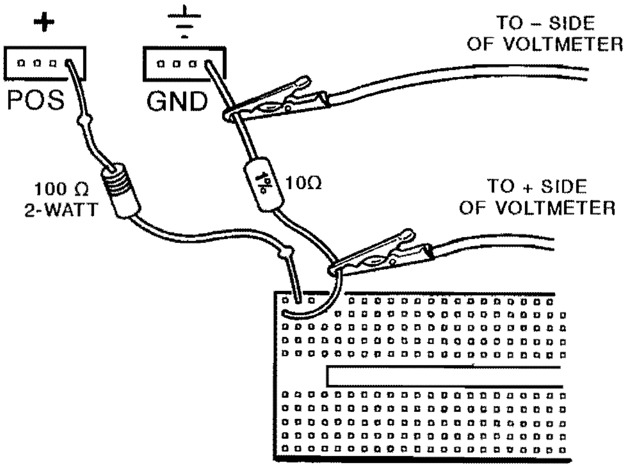


Figure 4-22

Circuit for Step 4 of Experiment 11.

5. Use the voltage value you set in Step 2 and the current value you measured in Step 3 (or Step 4) to compute the power that is dissipated in the circuit. The power is __________ watts.

6. Use the resistance value you measured in Step 1 and the voltage value you set in Step 2 to compute the power that is dissipated in the circuit. The power is __________ watts.

7. Use the resistance value you measured in Step 1 and the current value you measured in Step 3 (or Step 4) to compute the power that is dissipated in the circuit. The power is __________ watts.

8. Do the values of power you computed in Steps 5, 6, and 7 agree? ________.
Has the power rating of the resistor been exceeded? ___________.

9. Carefully touch the 100 ohm, 2-watt resistor with your finger. From this, it is obvious that the power is being dissipated in the form of ____________ .

10. Replace the 100 ohm, 2-watt resistor with the 100 ohm, 1/2-watt resistor. Assume that the 1/2-watt resistor has the same resistance value as the 2-watt resistor. Which dissipates the most power when it is connected into the circuit?

    ____________ .

11. After the circuit has been connected for a few minutes, carefully touch the 100 ohm, 1/2-watt resistor with your finger. Does it seem to be warmer or cooler than the 2-watt resistor that was used in Step 8? ____________ . Remove power from the resistor.

12. Has the power rating of the 1/2-watt resistor been exceeded? ____________ .

13. Switch the Trainer off.

Discussion

In Step 1, you measured the resistance of the 2-watt resistor. The value should be 100 ohms plus or minus five percent. In Step 2, you set the voltage to 10 volts. In Step 3, you measured the current. The current should be approximately:

$$I = \frac{E}{R} = \frac{10\ \text{V}}{100\ \Omega} = 0.1\ \text{A or } 100\ \text{mA}$$

If you did not have an ammeter, you constructed a makeshift ammeter in Step 4. The 10 ohm resistor develops an emf of 1 volt when the current through it is:

$$I = \frac{E}{R} = \frac{1\ \text{V}}{10\ \Omega} = 0.1\ \text{A or } 100\ \text{mA}$$

Thus, you can read the 0-1 V scale on the voltmeter as a 0-100 mA scale. With this ammeter, the current through the circuit should be slightly less than 100 milliamperes. The makeshift ammeter introduces an error of about 10 percent because it adds 10 ohms of resistance to the circuit.

In Steps 5, 6, and 7, you use the following equations to compute the power being dissipated:

$$P = EI\ ;\ P = \frac{E^2}{R}\ ;\text{ and } P = I^2R$$

In each case, the power should be about 1 watt. Notice that this does not exceed the power rating of the 2-watt resistor.

In Step 9, you saw that power is dissipated in the form of heat. The 2-watt resistor becomes quite warm. However, the resistor is large enough to safely dissipate the heat. In Step 10, you replaced the 2-watt resistor with a 1/2-watt resistor of the same resistance value. Because the resistors have the same resistance value, they both dissipate the same amount of power (1 watt). However, because the 1/2-watt resistor is smaller, the heat is concentrated in a smaller area. Thus, the 1/2-watt resistor becomes hotter to the touch. By forcing the 1/2-watt resistor to dissipate 1 watt, you exceeded the power rating by 100 percent. This causes the resistor to overheat. If you operate the resistor in this condition for extended periods, its value may change or the resistor may fail entirely.

EXPERIMENT 12

Maximum Power Transfer Theorem

OBJECTIVE: *To demonstrate that maximum power is obtained from a power source when the resistance of the load is equal to the internal resistance of the power source.*

Introduction

The maximum power transfer theorem states that maximum power is obtained from a power source when the resistance of the load is equal to the internal resistance of the power source. Or stated another way, maximum power is delivered to a load when the resistance of the load matches that of the power source. For example, assume that a power source has an internal resistance (R_{int}) of 100 ohms. It will deliver maximum power to a load when the resistance of the load (R_L) is exactly 100 ohms.

If you plot the value of R_L against the amount of power dissipated by R_L, the curve will look like the one shown in Figure 4-23. As the value of R_L approaches that of R_{int}, the amount of power dissipated increases. The dissipated power reaches maximum just at the point where $R_L = R_{int}$. Once R_L goes above the value of R_{int}, the dissipated power begins to decrease.

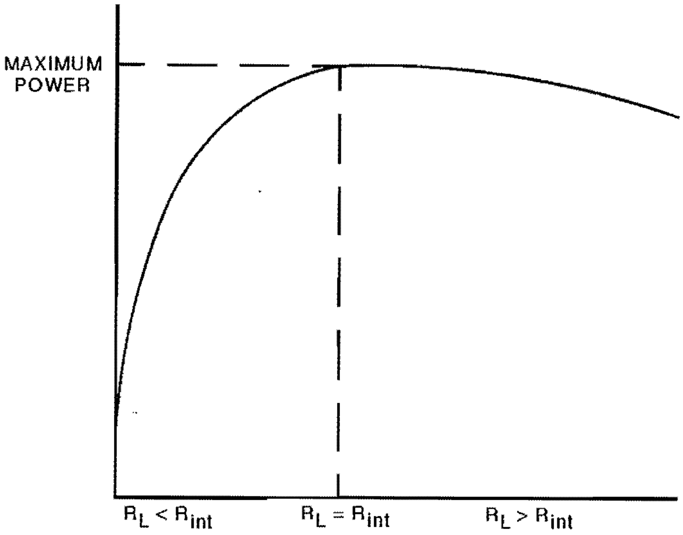


Figure 4-23

Power Transfer Curve.

You can use a power supply or a battery to demonstrate this principle. However, in most cases, the internal resistance of the power supply or battery is so small that extremely high currents will flow if the load resistance is matched to that of the power source. For example, a lead-acid cell may have an internal resistance of 0.01 ohms. Obviously, if you use this value of load resistance, the battery will quickly discharge.

However, there are many cases in electronics in which signal sources with relatively high internal resistances are used. In these cases, the resistance of the load can be matched to that of the signal source so that maximum power is transferred to the load.

The internal resistance of the power supply in your Trainer is too small to be used directly for experimentation. However, you can connect a fixed resistor in series with the Trainer's power supply to *simulate* a higher internal resistance. In the following experiment, you will connect a 100 ohm precision resistor in series with the power supply output. For purposes of the experiment, the internal resistance of the supply will be considered to be 100 ohms, and the *actual* internal resistance of the supply will be ignored. You will make power calculations as you vary the resistance of a 200 ohm load resistance, R_L in series with the 100 ohm R_{int}, to verify the Maximum Power Transfer Theorem. Your results should show that the power dissipated by the resistance of the load, P_L, is greatest when $R_L = R_{int}$.

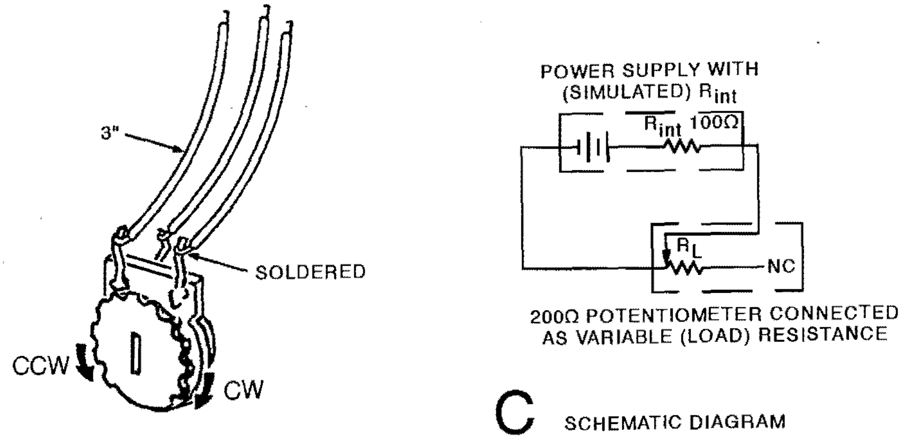
Material Required

1 — Heathkit Analog Trainer
1 — Multimeter with test leads
1 — 100 Ω, 1% resistor (brown-black-black-black-brown)
1 — 200 Ω, potentiometer (linear control #10-917)
Soldering iron and solder
#22 copper wire

Procedure

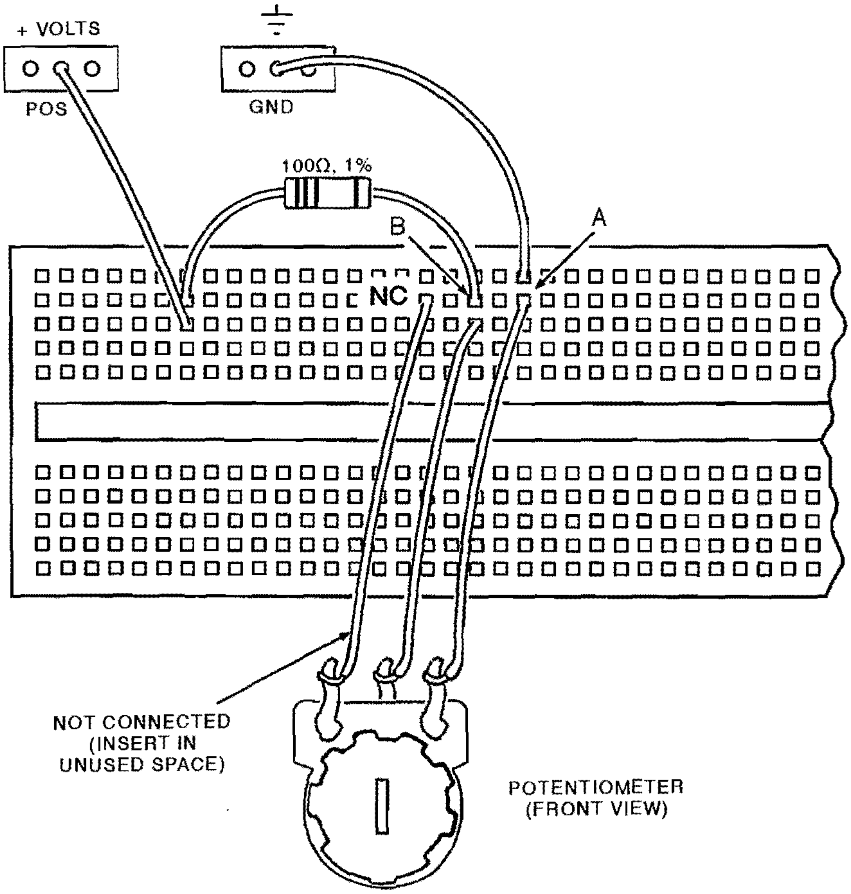
1. To prepare the 200 ohm potentiometer for breadboard connection, solder a 3-inch (both ends stripped 1/4-inch) wire to each of the three terminals on the pot as shown in Figure 4-24A.

2. Construct the circuit shown in Figure 4-24B. The schematic diagram for this circuit is shown in Figure 4-24C. Turn the knob of the 200 ohm potentiometer fully counterclockwise (ccw) to adjust it for *minimum* resistance. Check the circuit.


3"
SOLDERED
CCW
CW
POWER SUPPLY WITH
(SIMULATED) Rint
Rint 100Ω
RL
NC
200Ω POTENTIOMETER CONNECTED
AS VARIABLE (LOAD) RESISTANCE

A POTENTIOMETER PREPARATION

C SCHEMATIC DIAGRAM


+ VOLTS
POS
GND
100Ω, 1%
B
A
NC
NOT CONNECTED
(INSERT IN
UNUSED SPACE)
POTENTIOMETER
(FRONT VIEW)

B CONNECTION DIAGRAM

Figure 4-24

Maximum power transfer experiment wiring and schematic diagram.

3. Connect your voltmeter between the GND and +POS terminals. Switch the Trainer ON and adjust the +POS voltage control until the meter indicates +5 volts.

4. Break the circuit at point A (Figure 4-24B) and insert your ammeter after you set it to the 50mA DC, or greater, range. Refer to the table in Figure 4-25. The left column contains a list of current values. With the 200 ohm variable load set for minimum resistance (ccw), the current through the circuit should be approximately 50mA. The actual current measured is ____________ mA. Enter this as the first current value in the "MEASURED CURRENT" column of the table. Disconnect your ammeter, and reconnect the circuit as before.

5. Now, with the circuit conditions remaining from the previous step, set your meter to measure voltage at 1 volt or below. Measure the voltage between points A and B, as shown in Figure 4-24B. This is the voltage across the load, or *load voltage*. Enter this value (next to the current you recorded in the previous step) in the "MEASURED VOLTAGE" column of the table.

6. Disconnect the pot from the circuit at points A and B (Figure 4-24B). Set your meter to measure a resistance of 10 ohms or less. Measure the resistance of the pot and record this value (next to the voltage value you entered in the previous step) in the "MEASURED RESISTANCE" column of the table. Disconnect your ohmmeter and reconnect the pot to the circuit as before.

7. Break the circuit at point A (Figure 4-24B) and insert your ammeter as before. The current displayed should still be the same as the last one recorded. While you monitor the current, increase the resistance of the 200 ohm pot (slightly cw) to obtain the next lower current value stated in the "MEASURED CURRENT" column of the table. Disconnect your ammeter and reconnect the circuit at point A.

8. Measure the load voltage and enter its value in the table.

9. Without changing its currently set value, disconnect the pot from the circuit at points A and B (Figure 4-24B). Set your meter to measure resistance. Measure the load resistance and enter its value in the table. Reconnect the pot to the circuit as before.

10. Repeat steps 7 through 9 for all of the current values listed in the "MEASURED CURRENT" column of the table.

11. Break the circuit at point A (Figure 4-24B) and insert your ammeter as before. The current displayed should still be the same as the last one you recorded. While you monitor the current, increase the resistance of the 200 ohm pot to its maximum value, that is fully clockwise (cw). With the 200 ohm variable load set for maximum resistance (cw), the current through the circuit should be approximately 17 mA. The actual current measured is ____________ mA. Enter this as the last current value in the "MEASURED CURRENT" column of the table in Figure 4-25. Disconnect your ammeter, and reconnect the circuit as before.

MEASURED CURRENT	MEASURED VOLTAGE (V)	MEASURED RESISTANCE (Ω)	CALCULATED RESISTANCE (Ω)	CALCULATED POWER (mW)
CCW________mA				
45 mA				
40 mA				
35 mA				
30 mA				
25 mA				
20 mA				
CW________mA				

Figure 4-25
Experiment data table.

12. With the circuit conditions remaining from the previous step, repeat steps 8 and 9 to complete the measurement data for the table. When you finish, switch the Trainer OFF.

13. Use the measurements you entered into your table to calculate the resistance and power dissipation of the load. Enter the results in the "CALCULATED RESISTANCE" and "CALCULATED POWER" columns of the table. You may use the following formulas:

$$R_L = \frac{E}{I}$$

$$P_L = I^2R \text{ or } P_L = \frac{E^2}{R} \text{ or } P_L = EI$$

Your calculations for R_L (CALCULATED RESISTANCE) should be close to your measured values. You can expect slight differences between the "measured" and "calculated" values which are attributed to measurement error, instrument/component precision, etc. Your power calculations should range from a minimum value (occurring when R_L is minimum), up through a maximum value ($R_L = R_{int}$, = 100 ohms), and then decrease for values of R_L greater than 100 ohms.

14. Use your values of "CALCULATED RESISTANCE" and "CALCULATED POWER" to graph the power transfer curve on the grid in Figure 4-26. To do this, plot each point and then connect the points with a smooth curve. For example, if your first resistance value were 2 ohms, and your first power value were 4 mW, you would plot this point by starting at the origin of the grid (R = P = 0 in the lower left hand corner) and going to the right (along the resistance axis) one small square, and then up 4 small squares. The point would lie at the intersection where R = 2 ohms, and P = 4 mW. Notice that the grid in Figure 4-26 is subdivided into resistance increments of 2 ohms, and power increments of 1 mW.

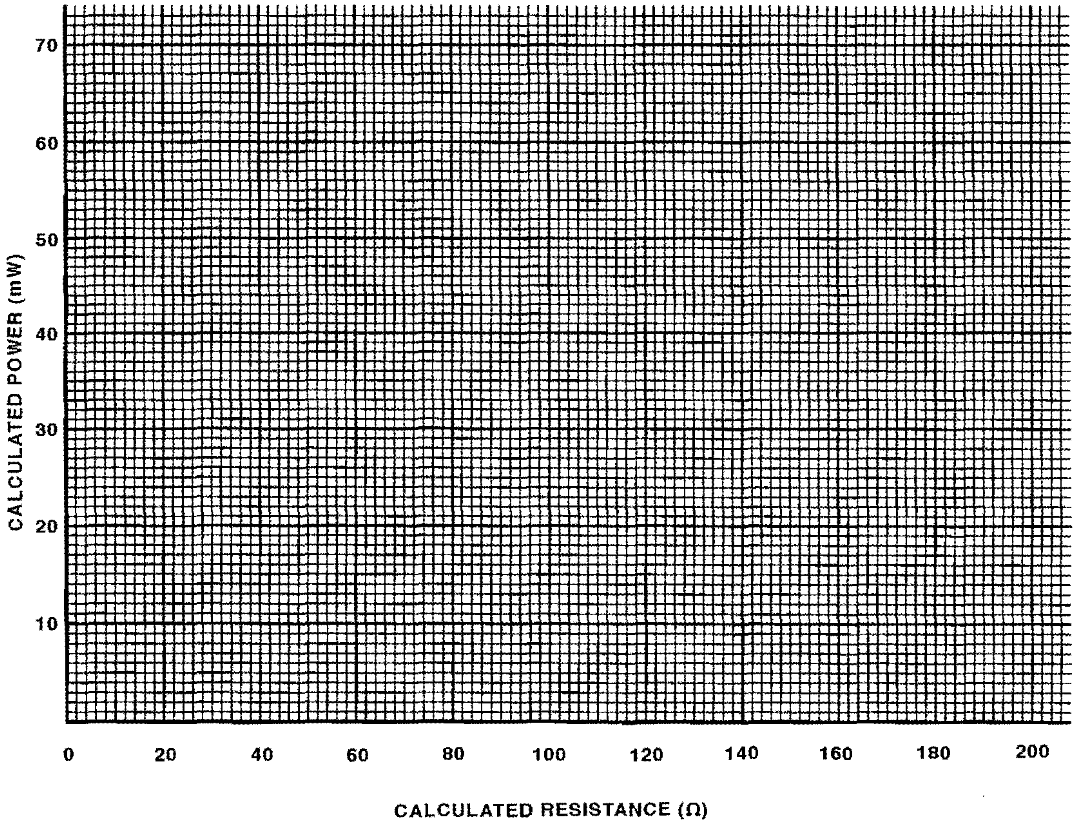


Figure 4-26

Maximum Power Transfer Curve.

Discussion

In practical applications, you will generally be concerned with the maximum power available to a specific load that is connected in series with a power supply that has some internal resistance. In this experiment, you verified the Maximum Power Transfer Theorem by simulating an internal resistance of 100 ohms and then measuring the power transfer characteristics of your Trainer with respect to an adjustable load resistance.

Because the internal resistance of the Trainer's power supply is too small to be effectively measured, you connected a 100 ohm precision resistor in series with the +POS supply that you set to 5 volts. By treating the *actual* R_{int} of the Trainer supply as negligible, you used the 100 ohms of the precision resistor as a *simulated* R_{int}.

After you measured the voltage drop across a variable (load) resistance (R_L), you were able to calculate the power dissipation of the load. You saw that the power dissipated by the load was less than maximum for load resistances either less than, or greater than, R_{int} (100 ohms). You also discovered that the maximum power is dissipated by the load when $R_L = R_{int}$ (or nearly so depending upon slight inaccuracies). The curve you plotted should have increased to a peak at $R_L = 100$ ohms and decreased beyond this. From these results, you verified that maximum power transfers to a load when the resistance of the load equals the resistance of the supply.

SUMMARY

The following is a point by point summary of this unit.

Ohm's Law defines the relationship between the three fundamental electrical quantities. It describes how current, voltage, and resistance are related.

Formulas are used to define the relationship. In these formulas, the letter I is used to represent current; E is used to represent voltage; and R is used to represent resistance.

The current formula states that current is equal to voltage divided by resistance. Or, stated as an equation:

$$I = \frac{E}{R}$$

The unit of current in the equation depends upon the units of voltage and resistance. If you assume that emf is expressed in volts, current is in amperes if the resistance is in ohms. However, the current is in milliamperes if the resistance is in kilohms. Finally, the current is in microamperes if the resistance is in megohms.

The voltage formula states that voltage is equal to the current multiplied by the resistance. That is, $E = I \times R$.

E is expressed in volts when I is in amperes and R is in ohms. E is also in volts when I is in milliamperes and R is in kilohms. Finally, E is in volts when I is in microamperes and R is in megohms.

The resistance formula states that resistance is equal to voltage divided by current. That is,

$$R = \frac{E}{I}$$

If you assume that E is given in volts, R is in ohms when I is in amperes. However, R is in kilohms when I is in milliamperes. Finally, R is in megohms when I is in microamperes.

While it is handy to remember which of the metric prefixes go together when you solve Ohm's Law problems, it is not absolutely essential. If you convert all quantities to volts, ohms, and amperes, you can solve any Ohm's Law problem without worrying about metric prefixes.

Power is the rate at which work is done. The unit of work is the joule while the unit of power is the watt. The watt is equal to one joule per second.

Expressed in English units, the watt is approximately equal to three-fourths of a foot-pound of work per second. The horsepower is equal to 746 watts or about three-fourths of a kilowatt.

The watt can also be expressed in terms of current and voltage. The watt is the amount of power that is expended when one volt of emf causes one ampere of current.

The letter P is used to represent power in equations. Power is equal to voltage multiplied by current. Or,

$$P = I \times E.$$

Power can also be expressed in terms of current and resistance or in terms of voltage and resistance. Figure 4-10 lists several important equations which involve power, current, voltage, and resistance. You should study this list carefully.

UNIT EXAMINATION

1. Ohm's Law states that current is:

   A. inversely proportional to voltage and directly proportional to resistance.
   B. inversely proportional to both voltage and resistance.
   C. directly proportional to both voltage and resistance.
   D. inversely proportional to resistance and directly proportional to voltage.

2. Which of the following is the correct equation for finding current when you know voltage and resistance?

   A. $E = I \times R$
   B. $I = E \times R$
   C. $I = \frac{E}{R}$
   D. $I = \frac{R}{E}$

3. Refer to Figure 4-27. What is the value of R_1?

   A. 10 ohms.
   B. 20 ohms.
   C. 0.5 ohms.
   D. 5 ohms.

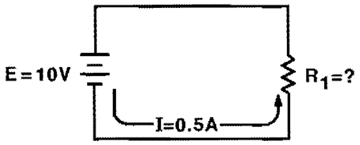


Figure 4-27
Circuit for Question 3.

4. What is the voltage drop across a 12 k ohm resistor when the current through the resistor is 2 milliamperes?

   A. 6 volts.
   B. 12 volts.
   C. 24 volts.
   D. 0.166 volts.

5. How much power is dissipated by a resistor which drops 6 volts when the current through it is 0.75 amperes?

   A. 6 watts.
   B. 4.5 watts.
   C. 8 watts.
   D. 0.125 watts.

6. Which of the following resistors dissipates the most heat?

A. A 125 ohm resistor which develops a voltage drop of 5 volts.
B. A resistor which develops a voltage drop of 25 volts when the current through the resistor is 0.25 amperes.
C. A 12 ohm resistor with a current of 2 amperes.
D. A 12 k ohm resistor with a current of 25 milliamperes.

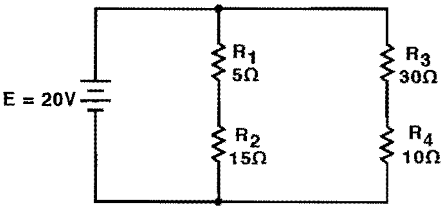


Figure 4-28
Circuit for Question 7.

7. Refer to Figure 4-28. Which resistor dissipates the most power?

A. R_1
B. R_2
C. R_3
D. R_4

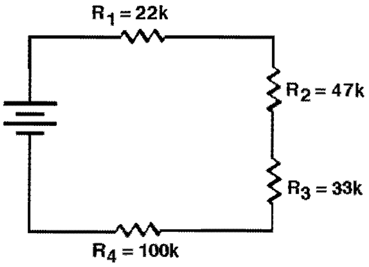


Figure 4-29
Circuit for Question 8.

8. Refer to Figure 4-29. Which resistor dissipates the most power?

A. R_1
B. R_2
C. R_3
D. R_4

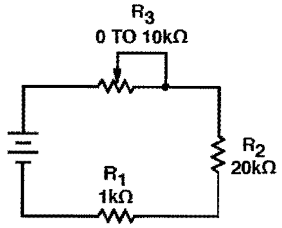


Figure 4-30
Circuit for Question 9.

9. Refer to Figure 4-30. You can find a fairly accurate indication of the current flowing in the circuit by measuring:

A. the voltage drop across R_1.
B. the voltage drop across the battery.
C. the voltage drop across R_3.
D. the resistance of R_3.

10. Ideally, the resistance of an ammeter should be:

A. 0 ohms.
B. 1000 ohms.
C. 100 ohms.
D. infinite.

11. The term for the rate at which work is done is:

A. current.
B. voltage.
C. power.
D. resistance.

12. Power use or loss in a circuit is called:

    A. dissipation.
    B. resistance.
    C. reactance.
    D. watts.

13. Which of the following is equal to .738 foot-pounds per second?

    A. Joule.
    B. Watt.
    C. Ampere.
    D. Coulomb.

14. What is the unit of mechanical power in the English system?

    A. Foot-pound.
    B. Joule.
    C. Horsepower.
    D. Ampere-volt.

EXAMINATION ANSWERS

1. D — Ohm's Law states that current is inversely proportional to resistance and directly proportional to voltage.

2. C — The correct formula for finding current when you know voltage and resistance is:

$$I = \frac{E}{R}$$

3. B — Since you know current and voltage but do not know R_1, the proper formula is:

$$R_1 = \frac{E}{I}$$

$$R_1 = \frac{10 \text{ volts}}{0.5 \text{ amps}}$$

$$R_1 = 20 \text{ ohms}$$

4. C — Use Ohm's Law:

$$E = I \times R$$

$$E = 2 \text{ mA} \times 12 \text{ k}\Omega$$

$$E = 24 \text{ volts}$$

5. B — Use the basic power formula:

$$P = I \times E$$

$$P = 0.75\text{A} \times 6 \text{ V}$$

$$P = 4.5 \text{ watts}$$

6. C — We must solve all four problems to see which resistor dissipates the most power (heat). In A, the voltage and resistance are given. Therefore, the proper formula is:

$$P = \frac{E^2}{R}$$

$$P = \frac{5^2}{125}$$

$$P = \frac{25}{125}$$

$$P = 0.2 \text{ watts}$$

In B, voltage and current are given. Thus:

$$P = I \times E$$

$$P = 0.25 \times 25$$

$$P = 6.25 \text{ watts}$$

In C, current and resistances are given. Therefore:

$$P = I^2 R$$

$$P = 2^2 \times 12$$

$$P = 4 \times 12$$

$$P = 48 \text{ watts}$$

In D, the same formula is used. However, you should first convert K ohms to ohms and milliamps to amps. Thus:

$$P = I^2 R$$

$$P = .025^2 \times 12000$$

$$P = .000625 \times 12000$$

$$P = 7.5 \text{ watts}$$

The resistor in answer C dissipates the most power.

7. B — There are several ways to solve this problem. The value of each resistor is given. Thus, if you can find the current, you can use the formula $P = I^2 R$. To determine the current through R_1 and R_2, finding the sum of these two resistances and divide this into the voltage:

$$I = \frac{E}{R}$$

$$I = \frac{E}{R_1 + R_2}$$

$$I = \frac{20 \text{ volts}}{5\,\Omega + 15\,\Omega}$$

$$I = \frac{20 \text{ volts}}{20\,\Omega}$$

$$I = 1 \text{ ampere}$$

Thus, R_1 dissipates:

$$P = I^2 R$$

$$P = 1^2 \times 5$$

$$P = 5 \text{ watts}$$

And, R_2 dissipates:

$$P = I^2 R$$

$$P = 1^2 \times 15$$

$$P = 15 \text{ watts}$$

Next you find the current through R_3 and R_4:

$$I = \frac{E}{R}$$

$$I = \frac{E}{R_3 + R_4}$$

$$I = \frac{20 \text{ volts}}{30\,\Omega + 10\,\Omega}$$

$$I = \frac{20 \text{ volts}}{40\,\Omega}$$

$$I = 0.5 \text{ amperes}$$

Now you can find the power that is being dissipated by R_3:

$$P = I^2 R$$

$$P = 0.5^2 \times 30$$

$$P = 0.25 \times 30$$

$$P = 7.5 \text{ watts}$$

And, R_4 dissipates:

$$P = I^2 R$$

$$P = 0.5^2 \times 10$$

$$P = 0.25 \times 10$$

$$P = 2.5 \text{ watts}$$

As you can see, R_2 dissipates the most power.

8. D — No voltage or current values are given in Figure 4-29, so you cannot determine the actual power being dissipated. However, because all of the resistors are connected in series, you know that the same current flows through all resistors. Furthermore, from the equation $P = I^2 R$ you know that the power being dissipated is directly proportional to resistance. Thus, the higher the resistance, the higher the power. Consequently, the largest resistor (R_4) must dissipate the most power. Another method you can use to solve the problem is to assume some value of current and determine the power being dissipated by each resistor.

9. A — R_1 is 1 k ohm resistor. Each milliampere of current through R_1 develops 1 volt of emf. Thus, the voltage developed across R_1 gives you an indication of the current flowing in the circuit.

10. A — Since the ammeter is connected in series with the power supply and load, the resistance of the ammeter should be as low as possible so that it does not change the current in the circuit. Ideally, the resistance of the ammeter should be 0 ohms.

11. C — Power is the rate at which work is done.

12. A — Power use or loss in a circuit is called dissipation. Since all components in a circuit, including the wire or conductors in the circuit, have some resistance and there is some current flowing through them, all components in a circuit must dissipate some power.

13. B — A joule is equal to .738 foot-pounds. It is a measure of work done. A watt is equal to .738 foot-pounds per second and is a measure of the rate at which work is done.

14. C — The horsepower is the unit of mechanical power in the English system. It is equal to 746 watts or 550 foot-pounds per second.

UNIT 5

MAGNETISM

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INTRODUCTION

In any study of electricity or electronics, you must consider the effects of magnetism. Electricity and magnetism are inseparable. Electric currents produce magnetic fields, and in special cases, magnetic fields produce electric currents. Electricity and magnetism are often considered to be two different aspects of a more general effect called *electromagnetic* phenomenon. Refer to the Unit Activity Guide to begin your study of magnetism.

UNIT OBJECTIVES

When you complete this unit, you will be able to:

1. Define the following terms: Field, permanent magnet, temporary magnet, flux lines, ferromagnetic, paramagnetic, diamagnetic, permeance, permeability, artificial magnet, natural magnet, flux density, field intensity, reluctance, ampere turn, magnetic induction, residual magnetism, retentivity, alternator, and DC generator.
2. List the four basic characteristics of flux lines.
3. State the left-hand rule for conductors, coils, and generators.
4. Name the common factor that links electricity and magnetism.
5. List the four factors that determine the amount of emf induced in a conductor and state how they relate to the induced emf.
6. List the four basic parts of a simple DC generator.
7. State the right-hand motor rule.
8. List ten electrical or electronic devices that use magnetism in one form or another and explain how they work.
9. State Faraday's law of magnetic induction.

UNIT ACTIVITY GUIDE

	Completion Time
☐ Read “The Magnetic Field.”	
☐ Complete programmed review frames I through 21.	
☐ Read “Electricity and Magnetism.”	
☐ Complete programmed review frames 22 through 43.	
☐ Read “Induction.”	
☐ Complete programmed review frames 44 through 62.	
☐ Read “Magnetic and Electromagnetic Applications.”	
☐ Complete programmed review frames 63 through 73.	
☐ Perform Experiment 13.	
☐ Perform Experiment 14.	
☐ Study Summary.	
☐ Complete Unit Examination.	
☐ Check Examination Answers.	

THE MAGNETIC FIELD

In science, action-at-a-distance is explained in terms of fields. For example, you learned that a charged particle can attract or repel another charged particle simply by coming close to it. A region of electrical influence extends outside each particle. This region of influence is called a *field.* Many scientists agree that an electrical field made up of lines of force exists around every charged particle.

This field concept also explains why certain metals can attract other metals. Everyone knows that a magnet attracts small pieces of iron or steel. A region of influence extends outside the magnet into the surrounding space. In this case, the region is called a *magnetic* field and is made up of *magnetic* lines of force. Thus, a magnet is a piece of material which has a magnetic field surrounding it.

Magnets

Magnets may be classified in several different ways. First, they can be classified according to the method by which they obtain their magnetic field. The first known magnets were *natural* magnets called magnetite or lodestone. These materials have a magnetic field in their natural state. *Artificial* magnets can be created from natural magnets. For example, if you rub soft iron repeatedly over a piece of lodestone, a magnetic field transfers to the iron. Another type of magnet is the electromagnet. An electric current produces its magnetic field. You will learn about the electromagnet in detail later.

Magnets are often classified by their shapes. Thus, there are horseshoe magnets, bar magnets, ring magnets, etc.

Some materials readily retain their magnetic fields for long periods of time. These are called *permanent* magnets. Other materials quickly lose their magnetism and are called *temporary* magnets. Both of these types find wide use in electronics.

Finally, magnets are classified by the type of material, such as metallic magnets or *ceramic* magnets. This is often carried even further and they are named according to the alloy used. Two popular classifications are Alnico (an alloy of aluminum, nickel, and cobalt) and Cunife (an alloy of copper, nickel, and iron).

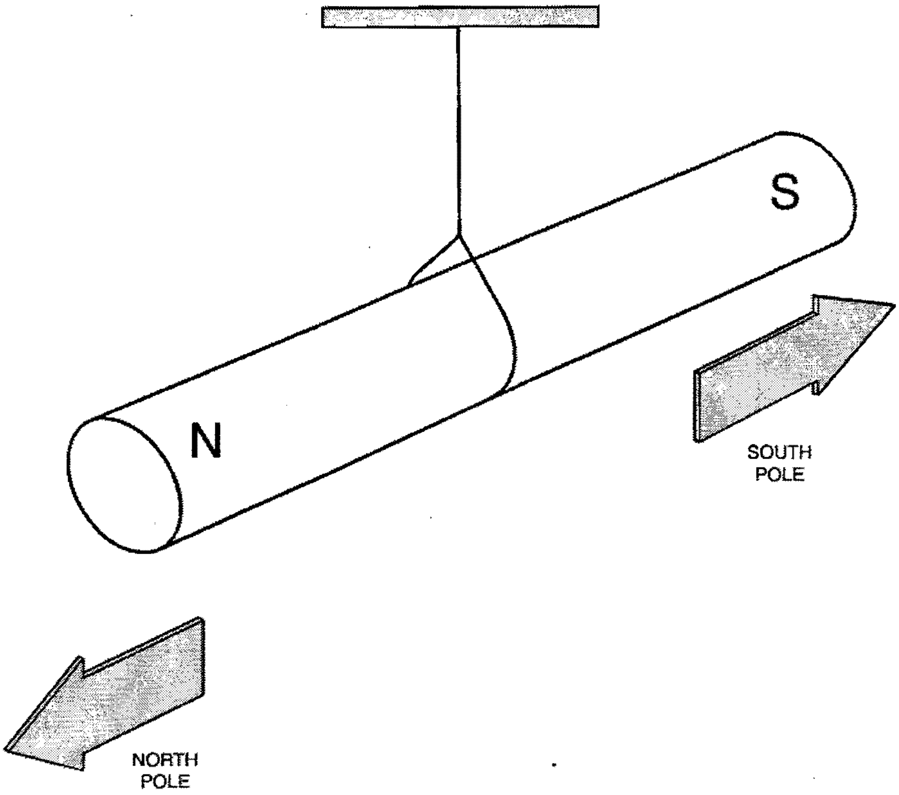

Figure 5-1
If a magnet is allowed to swing freely,
it aligns itself in a north-south direction.

The two ends of a magnet have different characteristics. One end is called a *south (S)* pole while the other is called a *north (N)* pole. One reason for choosing these names is that a bar magnet will align itself in a north-south direction if you allow it to hang freely as shown in Figure 5-1. The north (N) pole of the magnet is defined as that end which points toward the north pole of the Earth.

The magnet lines up in this way because the Earth itself is a huge magnet. As shown in Figure 5-2, it has its own magnetic field which influences any magnet on Earth. Mariners and explorers who rely on the magnetic compass have used this fact for centuries. The compass itself is nothing more than a tiny magnet balanced on a pin so that it rotates freely.

Magnets tend to align in a north-south direction according to a fundamental law of magnetism. This law states that like poles repel while unlike poles attract. Figure 5-3 illustrates this point. To see why magnets behave in this way, you must consider the nature of the magnetic lines of force.

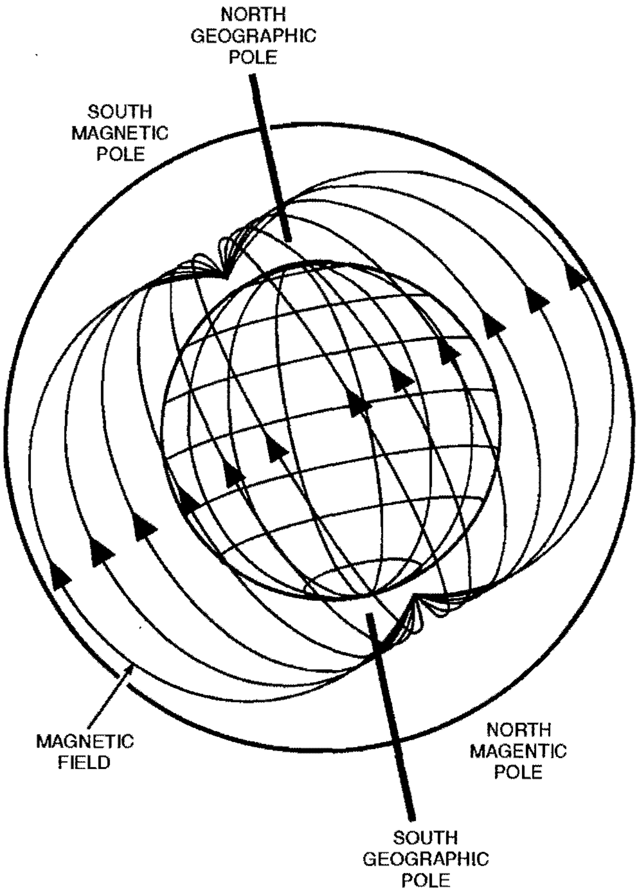
NORTH
GEOGRAPHIC
POLE
SOUTH
MAGNETIC
POLE
MAGNETIC
FIELD
NORTH
MAGENTIC
POLE
SOUTH
GEOGRAPHIC
POLE

Figure 5-2
The Earth's magnetic field.

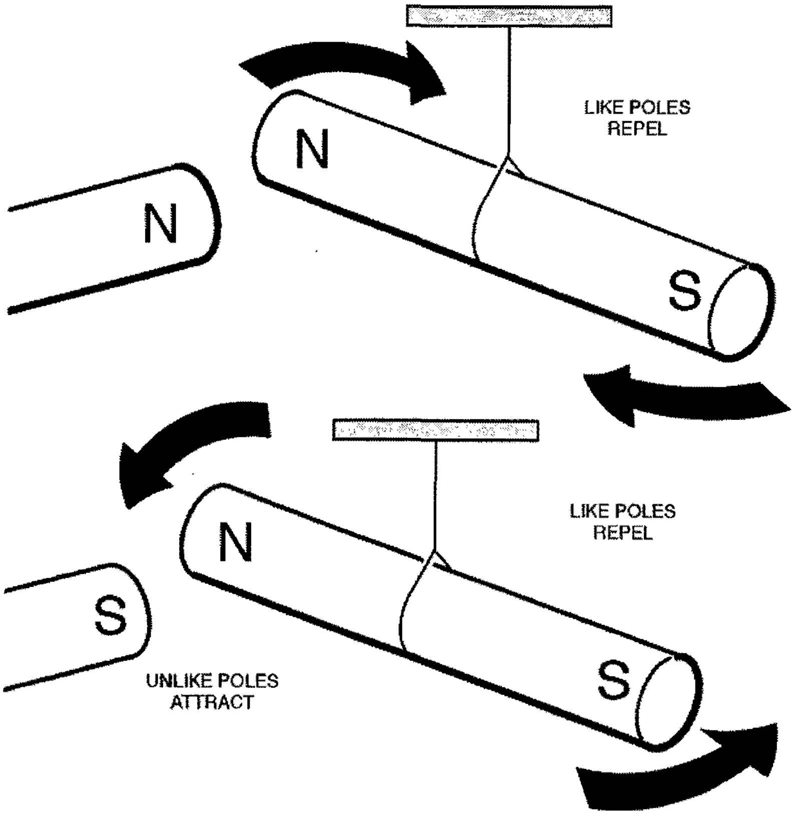
LIKE POLES
REPEL
N
N
S
LIKE POLES
REPEL
S
N
S
UNLIKE POLES
ATTRACT

Figure 5-3
Action of like and unlike poles.

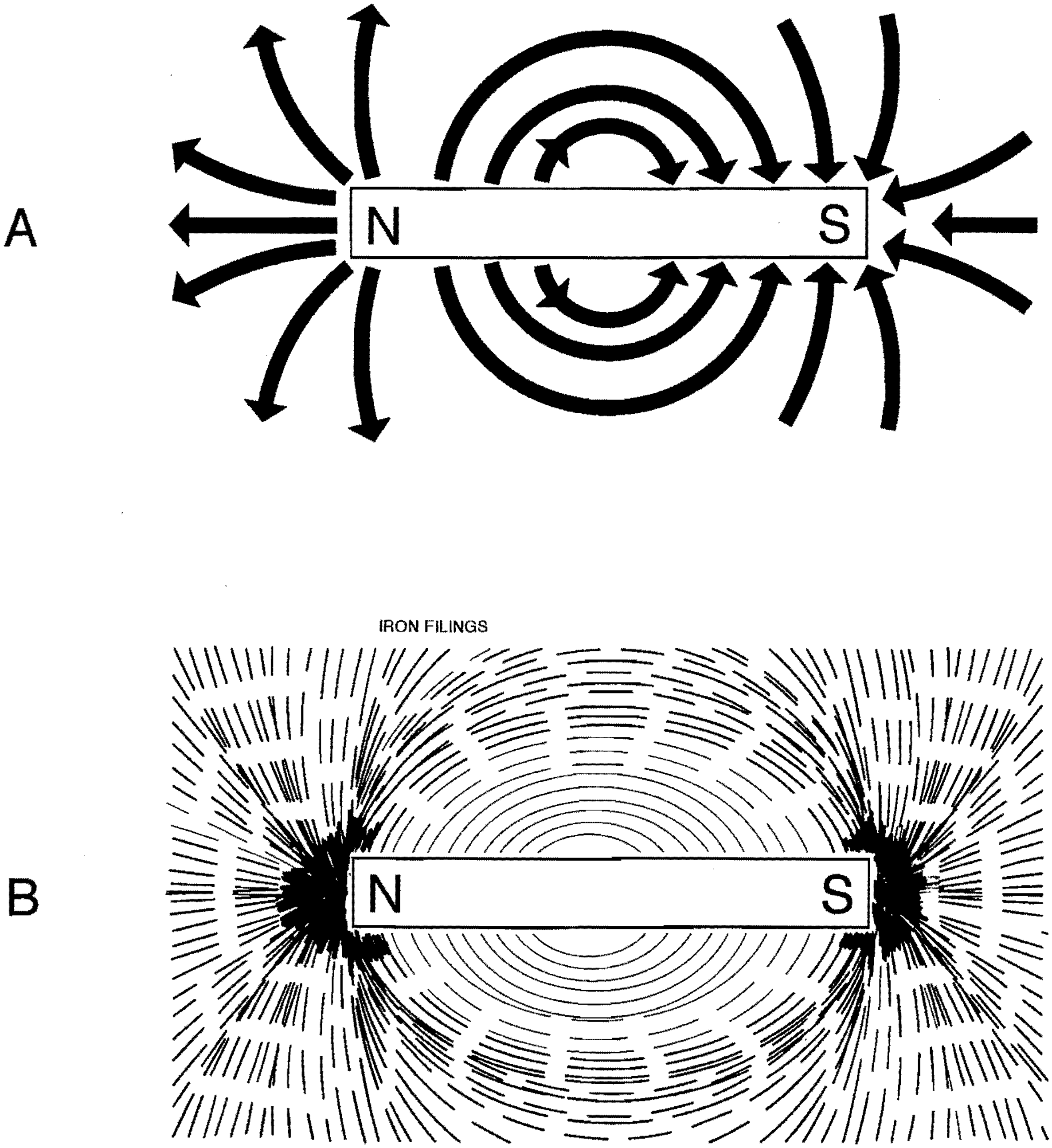
A
N
S
B
IRON FILINGS
N
S

Figure 5-4

Lines of force surround the magnet.

Lines of Force

To explain a magnetic field, scientists assume that lines of magnetic force called flux *lines* surround a magnet. Figure 5-4A shows the flux lines as they might appear around a bar magnet. While these lines are invisible, you can demonstrate their effects in several different ways. Figure 5-4B illustrates one of the most dramatic demonstrations. Iron filings are sprinkled evenly over a piece of paper. When you place the paper over the magnet, the filings align so that the effects of the lines of force are clearly visible.

There are several basic rules and characteristics of flux lines which you should know. Four of the most important are:

1. *Flux lines have direction or polarity.* The direction of the flux lines outside the magnet are arbitrarily assumed to be from the north pole to the south pole. Arrowheads often indicate this direction as shown in Figure 5-4A.

2. *The lines of force always form complete loops.* This may not be obvious from Figure 5-4A, but each line curves back through the body of the magnet to form a complete loop.

3. *Flux lines cannot cross each other.* This is the reason that like poles repel. Lines which have the same polarity can neither connect nor cross. When one field intrudes into another as shown in Figure 5-5A, the lines repel and the magnets tend to move apart.

4. *Flux lines tend to form the smallest possible loops.* This explains why unlike poles attract. Lines which have opposite polarity can link up as shown in Figure 5-5B. Then the loops attempt to shorten by pulling the two magnets together.

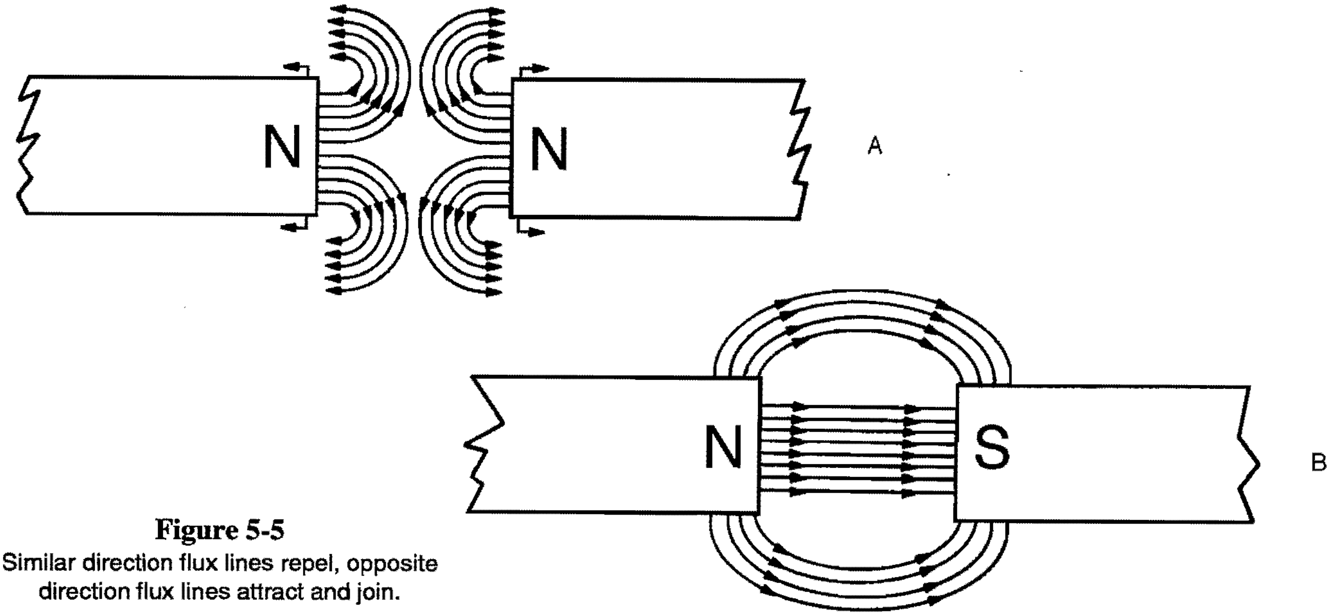

Figure 5-5
Similar direction flux lines repel, opposite direction flux lines attract and join.

Magnetic Materials

Of the 92 natural elements, only three respond readily to magnetic fields. These are iron, cobalt, and nickel. All three are metals and they have atomic numbers of 26, 27, and 28 respectively. Each has two valence electrons so their chemical and electrical characteristics are quite similar. In addition to these elements, there are dozens of alloys which have magnetic characteristics. Substances which readily respond to magnetic fields are called *ferromagnetic* substances. Ferromagnetic materials are strongly attracted by a magnetic field.

Most substances are classified as *paramagnetic*. These are substances which are attracted only slightly by a strong magnetic field. Generally, the force of attraction is so tiny, that these materials are considered to be non-magnetic. Substances such as air, aluminum, and wood are paramagnetic in nature.

Technically speaking, there is one other classification called *diamagnetic*. Diamagnetic materials are slightly repelled by magnetic fields. However, here again, the force of repulsion is so tiny that these materials are generally considered non-magnetic. Examples of diamagnetic materials are bismuth, quartz, water, and copper.

The characteristic which determines if a substance is ferromagnetic, paramagnetic, or diamagnetic is called *permeance* or *permeability*. Permeability refers to the ability of various materials to accept or allow magnetic lines of force to exist in them. Air is considered to be the standard with a permeability of 1. Other substances are given a permeability rating lower or higher than one, depending upon their magnetic characteristics. Iron is about 7000 times more effective in accepting flux lines than air. Consequently, iron has a permeability of about 7000. The table is Figure 5-6 shows the relative permeabilities of several different substances. Notice that those substances which have values of permeability less than 1 are diamagnetic and are slightly repelled by flux lines. Those having values slightly greater than 1 are paramagnetic and are slightly attracted by flux lines. Finally, those having permeabilities much higher than 1 are ferromagnetic and are strongly attracted by flux lines.

You can compare permeability of materials to the conductance in a circuit. Recall that conductance indicates the ease with which a material or circuit allows current to flow. In much the same way, permeability is the ease with which a material accepts lines of flux.

MATERIAL	PERMABILITY	CHARACTERISTIC	ACTION
BISMUTH	0.999833	DIAMETRIC	SLIGHTLY REPELLED
WATER	0.999991	DIAMETRIC	SLIGHTLY REPELLED
COPPER	0.999995	DIAMETRIC	SLIGHTLY REPELLED
AIR	1.000000	PARAMAGENTIC	NON-MAGENTIC
OXYGEN	1.000002	PARAMAGENTIC	SLIGHTLY ATTRACTED
ALUMINUM	1.000021	PARAMAGENTIC	SLIGHTLY ATTRACTED
COBALT	170.	FEROMAGNETIC	STRONGLY ATTRACTED
NICKEL	1000.	FEROMAGNETIC	STRONGLY ATTRACTED
IRON	7000.	FEROMAGNETIC	STRONGLY ATTRACTED
PERMALLOY*	100,000.	FEROMAGNETIC	STRONGLY ATTRACTED
SUPERMALLOY**	1,000,000.	FEROMAGNETIC	STRONGLY ATTRACTED

* PERMALLOY-AN ALLOY OF 17% IRON, 4% MOLYBDENUM, 79% NICKEL.
** SUPERMALLOY-AN ALLOY OF 16% IRON, 5% MOLYBDENUM, 79% NICKEL.

Figure 5-6
Relative permeabilities of materials.

You will now learn why permeability is so important. Figure 5-7A shows a permanent magnet surrounded by its lines of flux. Figure 5-7B shows how the flux lines are distorted when a piece of iron is brought near the magnet. Since iron has a high permeability, it can support lines of flux much more easily than the surrounding air. Consequently, a large number of the flux lines pass through the iron bar. At the same time, the lines attempt to contract to the smallest possible loops. This tends to attract the iron bar to the magnet.

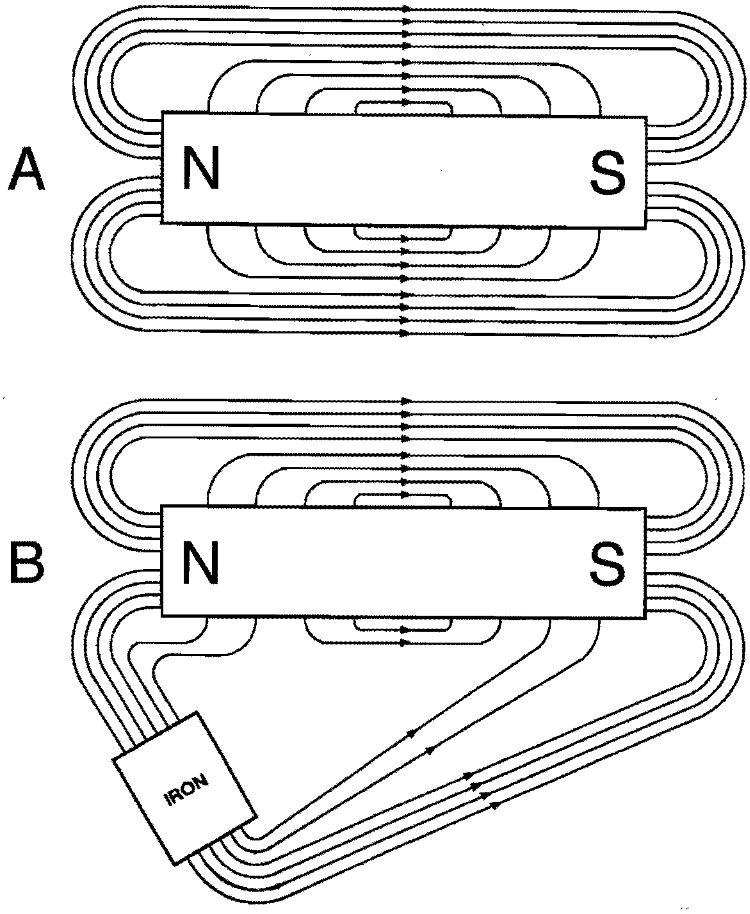

Figure 5-7
The flux lines pass through iron more easily than they do through air.

Theory of Magnetism

While it is difficult to explain exactly what magnetism is, a theory has been developed which explains the observed phenomenon. As with the basic theories of electricity, this one starts with the electron. You have seen that electrons orbit the nucleus of the atom in much the same way that the Earth orbits the sun. It also appears that the electron spins on its axis as shown in Figure 5-8A in much the same way that the Earth does. You have also seen that electrons have an electrostatic field as shown in Figure 5-8B. It appears to be a fact of nature that a moving electrical charge produces a magnetic field. The magnetic field produced by the spinning charge exists as concentric circles around the electron as shown in Figure 5-8C. The direction of the magnetic field depends upon the direction of spin of the electron. At any given point, the electrostatic field is at right angles to the magnetic field. These combined fields at right angles are often called an *electromagnetic field.* Figure 5-8D shows the complete picture of the electron.

You have seen that iron, nickel, and cobalt are the only natural magnetic elements. Each of these elements has two valence electrons. In other substances, the electrons tend to pair off with electrons of *opposite* spin. This means that the electrons have opposite magnetic characteristics which tend to cancel. However, in iron, nickel, and cobalt the two valence electrons have the same direction of spin. Consequently, their magnetic fields do not cancel; they add. Thus, an atom of iron, nickel, or cobalt has a net magnetic field.

Small groups of these atoms tend to form tiny permanent magnets called magnetic *domains*. When they are not in the presence of a magnetic field, these domains are arranged haphazardly as shown in Figure 5-9A. Because, the domains are turned at odd angles, the net magnetic effect is zero. You can magnetize a piece of metal such as this by subjecting it to a strong magnetic field. As shown in Figure 5-9B, this causes all the domains to align in the same direction. When all of the domains are aligned in a common direction, the entire piece of metal becomes a magnet.

There are several experiments which seem to verify the domain theory. The first is shown in Figure 5-10A. If a bar magnet is cut into several pieces, each piece becomes a complete magnet having both a north and a south pole. Figure 5-10B shows another experiment. When you hit the magnet with a hammer, the domains are jarred back into a random pattern and the net magnetism becomes lost. Figure 5-10C shows that the same thing happens when you heat the magnet. The heat energy causes the domains to vibrate enough to rearrange themselves in a random pattern. The electron's role in magnetism.

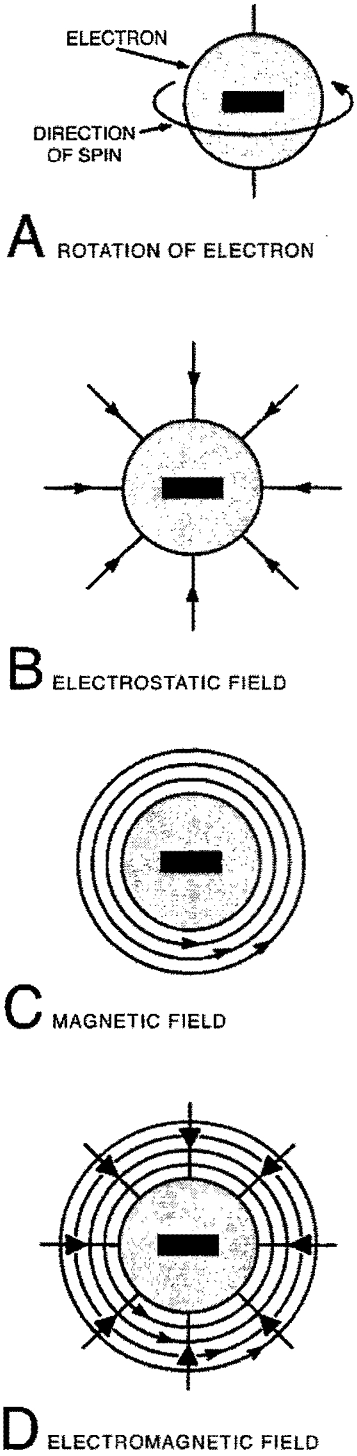

Figure 5-8
The electron's role in magnetism.

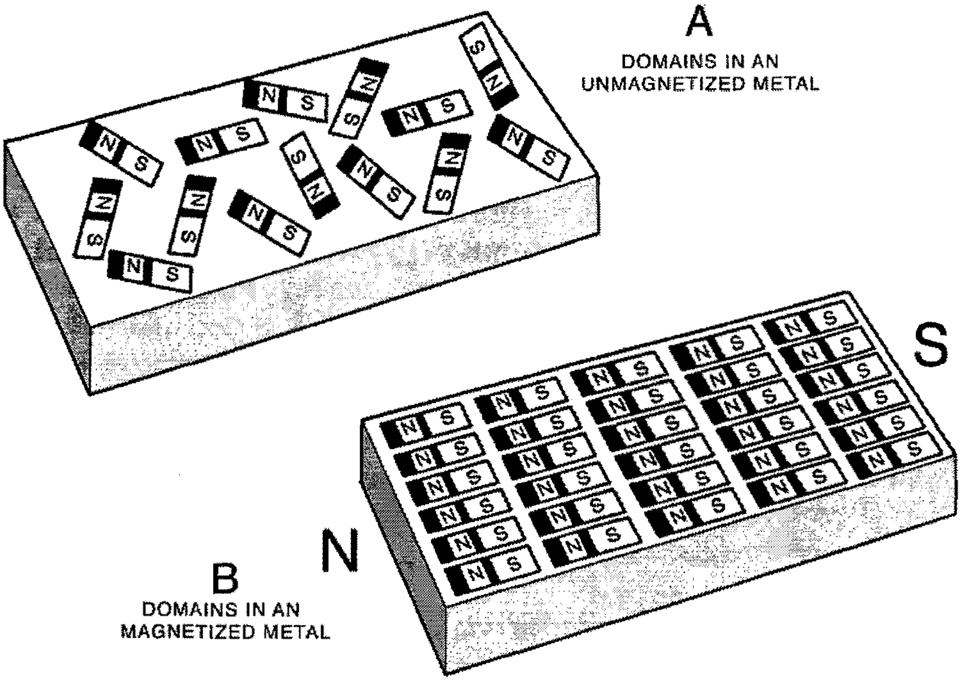
A
DOMAINS IN AN UNMAGNETIZED METAL
B
DOMAINS IN AN MAGNETIZED METAL
N
S

Figure 5-9
Alignment of magnetic domains.

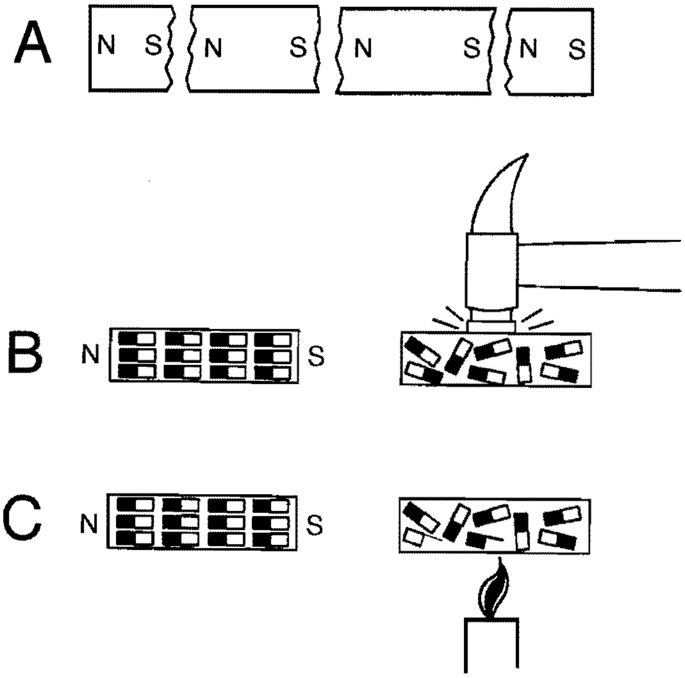
A
N S
N S
N S
N S
B
N
S
C
N
S

Figure 5-10
These experiments seem to verify the domain theory of magnetism.

Programmed Review

1. The region of influence around a magnet is called a __________ __________.

2. (magnetic field) This magnetic field is made up of __________ lines of force or flux lines.

3. (magnetic) Thus, a magnet is a device which is surrounded by a __________ __________.

4. (magnetic field) You can find some magnets in nature. Lodestone is an example of a natural __________.

5. (magnet) However, most magnets are man-made. These are referred to as __________ magnets.

6. (artificial) A permanent magnet is one which remains magnetized for long periods of time while a __________ magnet is one which loses its magnetism very quickly.

7. (temporary) If a magnet is allowed to swing freely, it will align itself so that its __________ pole points toward the north pole of the Earth.

8. (north) A common device which works on this principle and is used to indicate direction is called a __________.

9. (compass) A basic rule of magnetism is that like poles ____________ while unlike poles ____________ .

10. (repel, attract) You can classify all materials according to their magnetic characteristics. A material which is readily magnetized is called ____________ .

11. (ferromagnetic) A material which is only slightly attracted by a very strong magnetic field is classified as ____________ .

12. (paramagnetic) A material which is slightly repelled by a strong magnetic field is classified as ____________ .

13. (diamagnetic) Only three elements are naturally ferromagnetic. These are ____________, ____________, and ____________ .

14. (iron, nickel, and cobalt) The property that determines a material's magnetic characteristic is called permeance or ____________ .

15. (permeability) Permeability is defined as the ease with which a substance will accept ____________ lines.

16. (flux) A commonly accepted theory of magnetism assumes that the magnetic field is initially caused by the ____________ spinning on its axis.

17. (electron) In most elements, about half the electrons spin in one direction while the other half spin in the opposite direction. The net effect is that the magnetic fields ____________ .

18. (cancel) However, in iron, cobalt, and nickel, the two valence electrons spin in the same direction. The result is that these atoms have a net ____________ field.

19. (magnetic) These magnetic atoms tend to bunch together in tiny groups called magnetic ____________ .

20. (domains) Normally, these domains are arranged haphazardly. However, when they are subjected to a magnetic field, the domains align in the same direction. Thus, the piece of metal becomes a ____________ .

21. (magnet)

ELECTRICITY AND MAGNETISM

Electricity and magnetism are closely related. The electron has both an electrostatic field and a magnetic field. This may lead you to conclude that a charged object should have a magnetic field. However, this is not the case, since the magnetic field of about half of the electrons are opposite to the other half. Nevertheless, the electron plays an important part in magnetism. It can be forced to produce a magnetic field in substances which are normally considered non-magnetic, such as copper and aluminum. The key is *motion.* Motion is the catalyst which links electricity and magnetism. Anytime a charged particle moves, a magnetic field is produced. If a large number of charged particles can be moved in a systematic way, a usable magnetic field is formed. You have seen that current flow is the systematic movement of large numbers of electrons. Thus, current flow causes a magnetic field.

Current Flow and Magnetism

When current flows through a wire; a magnetic field is developed around the wire. The field exists as concentric circles as shown in Figure 5-11. While this field has no north or south pole, it does have direction. The direction of the field depends upon the direction of current flow. The arrow heads on the flux lines indicate their direction. This does not mean that the flux lines are *moving* in this direction. It simply means that they are *pointing* in this direction.

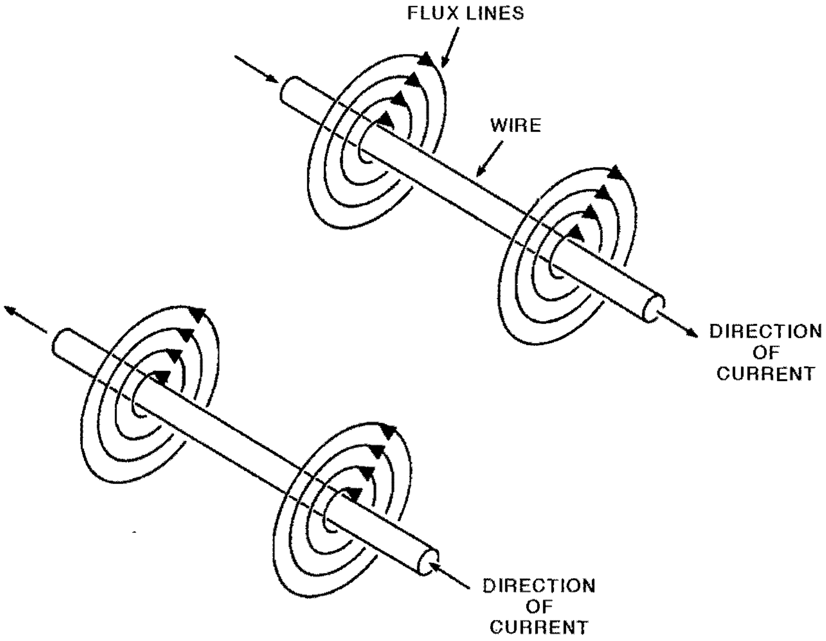

Figure 5-11
Flux lines exist as concentric circles around a current-carrying conductor.

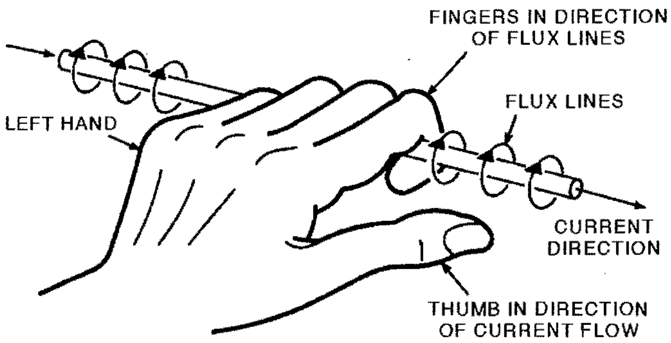
FINGERS IN DIRECTION OF FLUX LINES
FLUX LINES
LEFT HAND
CURRENT DIRECTION
THUMB IN DIRECTION OF CURRENT FLOW

Figure 5-12
Left-hand magnetic field rule.

You can determine the direction of the flux lines if you know the direction of the current flow. The rule for determining this is called the *left-hand magnetic-field rule* or the *left-hand rule for conductors*. It is illustrated in Figure 5-12. This rule states:

If you grasp the conductor in your *left* hand with your thumb pointing in the direction of current electron flow through the conductor, your fingers now point in the direction of the flux lines.

Study Figure 5-12 until you understand this rule. Try this rule on the two conductors shown in Figure 5-11.

To explain some aspects of electromagnetism, it is helpful to show current flow in a third dimension. To do this, two new symbols are necessary. Figure 5-13A shows current flowing into the page. If you view the wire from the end, the tail of the arrow appears as a cross as shown in Figure 5-13B. This cross represents current flowing into the page. If you view this wire from the end, the head of the arrow appears as a round dot as shown in Figure 5-13D. The dot represents current flowing out of the page.

Figure 5-14 uses these new symbols to show how opposite and similar currents establish magnetic fields. In Figure 5-14A, opposite currents are shown. Use the left-hand rule to verify the direction of the two magnetic fields. Since the fields point in opposite directions, they tend to repel each other. Figure 5-14B shows that the opposite situation exists when the two currents flow in the same direction. Here, the fields point in the same direction. Thus, they are free to connect. This tends to draw the two fields together.

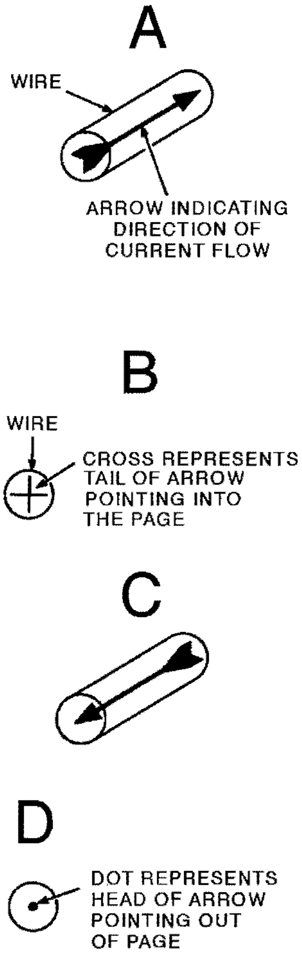
A
WIRE
ARROW INDICATING DIRECTION OF CURRENT FLOW
B
WIRE
CROSS REPRESENTS TAIL OF ARROW POINTING INTO THE PAGE
C
D
DOT REPRESENTS HEAD OF ARROW POINTING OUT OF PAGE

Figure 5-13
Developing two new symbols to represent current flow in a third dimension.

As long as the conductor is a straight piece of wire, the magnetic field produced is of little practical use. Although it has direction, it has no north or south pole. Also, unless the current is extremely high, the magnetic field has little strength. However, by changing the shape of the wire, we can greatly improve its magnetic characteristics.

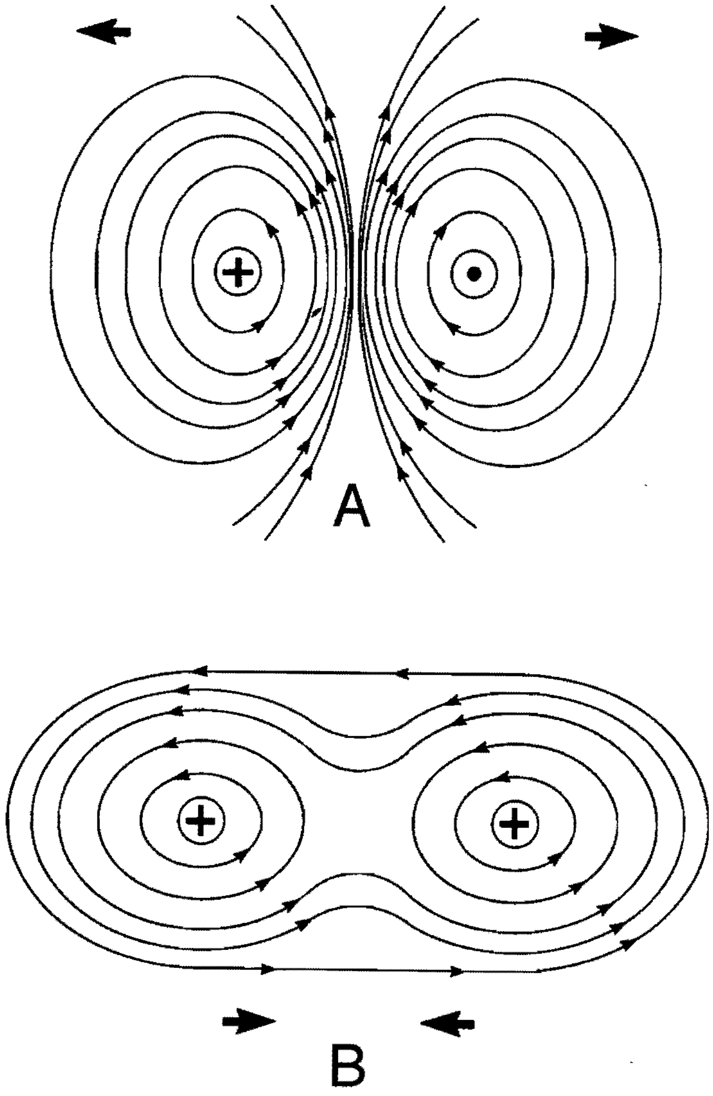

Figure 5-14
Opposite currents cause opposite fields which repel. Currents in the same direction cause fields which add and attract.

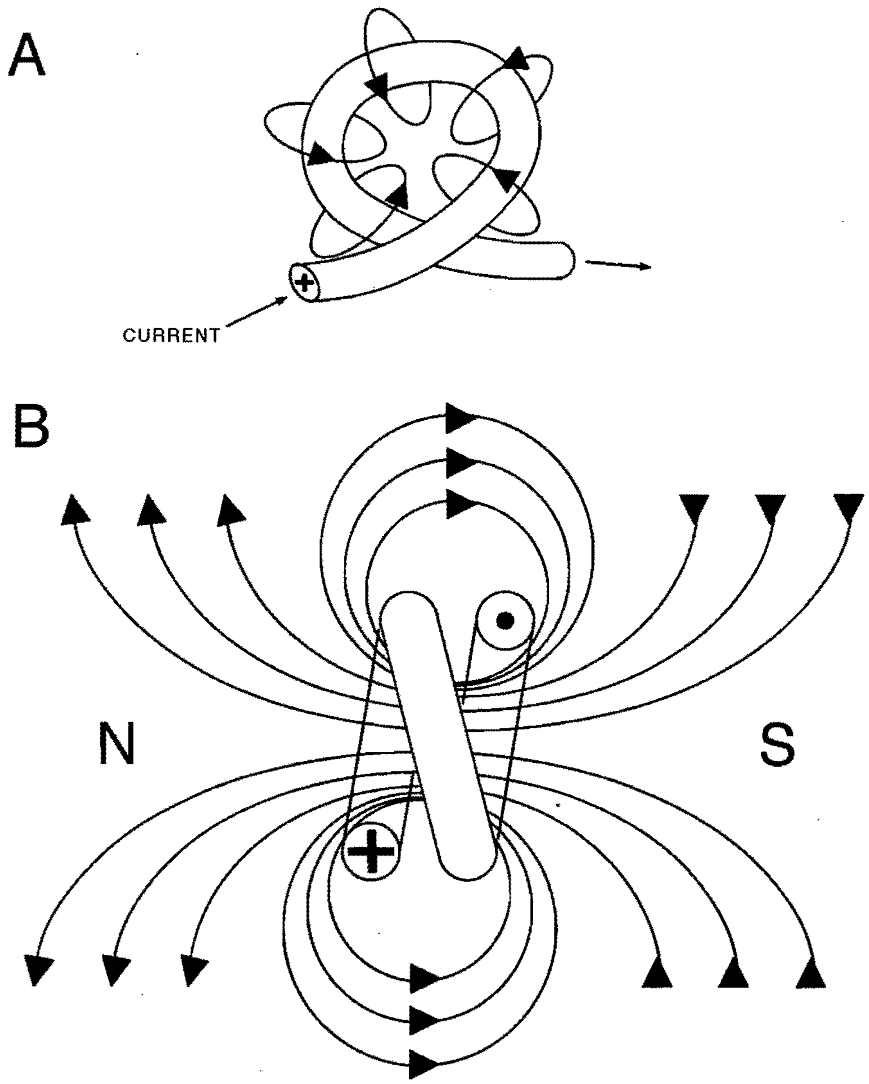

Figure 5-15
Flux lines around a loop of wire.

Figure 5-15 shows two views of a short piece of wire twisted into a loop. Simply forming the loop helps the magnetic characteristics in three ways. First, it brings the flux lines closer together. Second it concentrates the majority of the flux lines in the center or *core* of the loop. Third, it creates north and south poles. The north pole is the side where the flux lines come out; the south pole, the side where they go in. Thus, this loop of wire has the characteristics of a magnet. In fact, this is an example of a simple electromagnet.

The Electromagnet

Electromagnetism is used in many different electronic devices. In its simplest form, the electromagnet is nothing more than a length of wire wrapped in coils as shown in Figure 5-16. When current passes through the wire, a magnetic field is established. Because the turns of wire are very close together, the flux lines of the individual turns add together, to produce a very strong magnetic field. The more turns in the coil, the more flux lines there are to add together. Also, when more current flows through the coil, there will be more flux lines. Consequently, the strength of the magnetic field is directly proportional to both the number of turns in the coil and the amount of current through the coil.

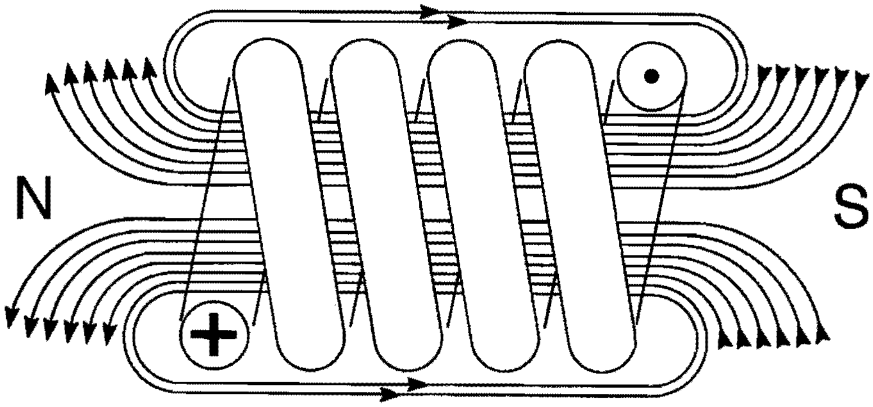

Figure 5-16
Magnetic filed around a coil.

The magnetic field around the coil has the same characteristics of the magnetic field around a permanent magnet. However, one difference is that the field around the coil exists only when current flows through the coil. Another important difference is that you can change the amount of current that flows through the coil to vary the strength of the magnetic field around the coil.

You learned two ways to increase the strength of the magnetic field around an electromagnet. One way is to increase the current. Another is to increase the number of turns. However, a third method is the most dramatic of all. It involves adding a bar of ferromagnetic material, called a core, to the center of the coil. For example, if you slip an iron core into the coil shown in Figure 5-16, the strength of the magnetic field greatly increases. That happens because the iron core has a much higher value of permeability than air. Consequently, the iron core can support many times more flux lines than air. Most electromagnets are made by winding many turns of wire around a bar of ferromagnetic material such as iron.

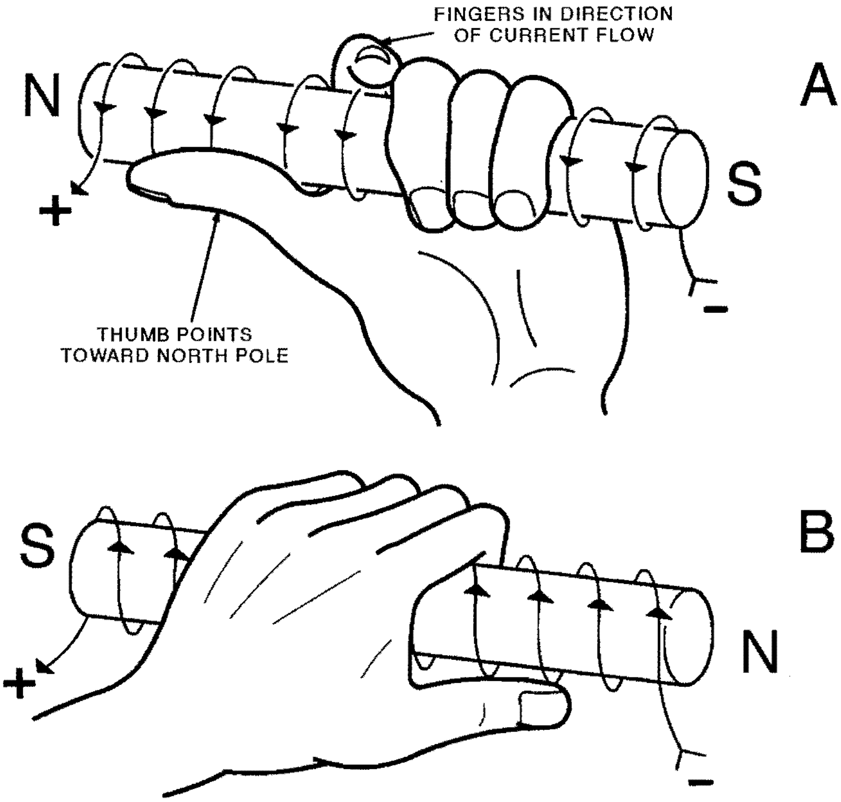
FINGERS IN DIRECTION OF CURRENT FLOW
N
A
S
+
-
THUMB POINTS TOWARD NORTH POLE
S
B
N
+
-

Figure 5-17
Left-hand rule for coils.

It is often helpful to know the polarity of an electromagnet. You can easily determine this if you know the direction of current through the coil. The rule is called the *left-hand rule for coils* and is illustrated in Figure 5-17. The rule states:

> "If you grasp the coil with your left hand in such a way that your fingers are wrapped around it in the same direction that current is flowing; your thumb will then point toward the north pole of the magnet."

Remember that current flows from negative to positive. In Figure 5-17A, the current flows up the back side of the coil and down the front side. If you wrap your fingers in this direction, your thumb points to the left. Thus, the left end of the electromagnet is the North Pole. In Figure 5-17B, the coil is wrapped in the opposite direction and the north pole is on the right.

You can use this same procedure to determine the direction of current flow if you know which end is the north pole. Assume that you know the north pole is on the right but you do not know the direction of current. You simply grasp the coil in your left hand with your thumb pointing toward the north pole of the coil. Your fingers now point in the direction of current flow.

Magnetic Quantities

In your study of electricity, you used electrical quantities such as voltage, current, resistance, conductance, and power. In much the same way, studying magnetism requires that you learn several magnetic quantities. Of particular importance are the magnetic quantities: flux, flux density, magnetomotive force, field intensity, reluctance, and permeability. While the definitions of these quantities are straight forward, the units of measure for these quantities often become confusing. The reason for this is that three different systems of measurements have been used over the years. The first is the English system which uses the familiar inches, pounds, etc. The two other systems are based upon metric units. One is called the *cgs* system. Cgs stands for centimeter, gram, and second. Another system based upon metric units is the *mks* system. Mks stands for meter, kilogram, and second. In the following discussion, the English units is used because this is probably the system with which you are most familiar. At the end of this section, the English units are compared with the metric units.

Flux. The complete magnetic field of a coil or a magnet is known as the *flux*. Thus, the flux is the total lines of magnetic force. The Greek letter *phi* (ϕ) denotes flux. In the English system, flux is measured in lines. A coil or magnet which produces 1000 lines of force has a flux of 1000 lines or 1 kiloline ($\phi = 1$ K lines).

Flux Density. As the name implies, *flux density* refers to the number of lines per unit of area. In the English system, the unit of area is the square inch. Thus, flux density is expressed as the number of lines per square inch. The letter B represents flux density. If a coil with a cross sectional area of two square inches has a flux of 1000 lines, the flux density is 1000/2 or 500 lines per square inch ($B = 500$ lines/in^2).

Magnetomotive Force (mmf). Magnetomotive force is the force which produces the flux in an electromagnet or coil. As you have seen, this force is directly proportional to the number of turns in the coil and the amount of current flowing through the coil. For this reason, the unit of mmf is the ampere-turn. This is the amount of force developed by one turn of wire when the current is one ampere. For example, a coil that has 50 turns and a current of 2 amperes has a magnetomotive force of $50 \times 2 = 100$ ampere turns.

Field Intensity or Magnetizing Force. While mmf is a useful term, it is limited in application because it does not take into consideration the length of the coil. Thus, a coil with 50 turns may be 1 inch long or 10 inches long and still have the same mmf. Obviously though, the magnetic field is concentrated in a much smaller space with the shorter coil.

Field intensity takes into consideration not only the mmf but also the length of the coil. Field intensity is expressed as ampere turns per inch and is represented by the letter H. For example, if a 2-inch coil has an mmf of 100 ampere turns, the field intensity is 100/2 or 50 ampere turns per inch (H = 50 amp-turns/in). Field intensity is sometimes called *magnetizing force* which should not be confused with magnetomotive force.

Permeability. You have already learned about this important characteristic. Recall that permeability is the ease with which a material can accept lines of force. You can also think of it as the ability of a material to concentrate a large number of force lines in a small area. For example, a 1-inch column of soft iron can hold hundreds of times more flux lines than a comparable column of aluminum. The Greek letter mu (μ) represents permeability.

Reluctance. The opposite or reciprocal of permeability is called *reluctance* and is represented by the letter R. Reluctance is generally defined as an opposition to flux. Thus, a material with high reluctance is reluctant to accept flux lines. Since reluctance is the reciprocal of permeability, it may be expressed by the equation:

$$R = \frac{1}{\mu}$$

For example, soft iron has a permeability of 2700. Thus, it has a reluctance of 1/2700. Since air has a permeability of 1, it has a reluctance of 1/1 or 1. Flux lines tend to follow the path of least reluctance.

Ohm's Law for Magnetic Quantities

Three of the above quantities are related by an equation which is very similar to the Ohm's Law equation. In fact, you can compare these three magnetic quantities to the electrical units of current, voltage, and resistance. In this analogy, current corresponds to magnetic flux (ϕ). Recall that flux is produced by magnetomotive force (mmf). Consequently, mmf corresponds to voltage. Finally, the opposition to flux is called reluctance (*R*). Flux, mmf, and reluctance are related by the equation:

$$\phi = \frac{\text{mmf}}{R}$$

This states that the magnetic flux developed in a core material is directly proportional to the magnetomotive force and inversely proportional to the reluctance. Since this equation is similar to the Ohm's Law equation discussed earlier, it is often called the Ohm's Law for magnetic circuits.

Comparison of Units

As you saw, there are three systems of measurements in common use. The most familiar is the English system. However, the metric system is becoming increasingly popular. Unfortunately, the units for the various magnetic quantities are different in each system. The table shown in Figure 5-18 compares the various units.

In the English system, flux is measured in lines or kilolines; flux density is measured in kilolines per square inch; mmf is measured in ampere-turns; and field intensity is measured in ampere-turns per inch.

TERM	DESCRIPTION	SYMBOL	ENGLISH UNITS	CGS UNITS	MKS UNITS
FLUX	TOTAL LINES OF FLUX	Ø	LINES OR KILOLINES	MAXWELL 1 MAXWELL = 1 LINE	WEBER 1 WEBER = 100,000,000 LINES
FLUX DENSITY	LINES PER UNIT AREA	B	$\frac{\text{KILOLINES}}{\text{IN}^2}$	GAUSS $1\ \text{GAUSS} = \frac{1\ \text{MAXWELL}}{\text{CM}^2}$	$\frac{\text{WEBER}}{\text{M}^2}$
MAGNETOMOTIVE FORCE	TOTAL FORCE THAT PRODUCES FLUX	MMF	AMPERE-TURN	GILBERT 1 GILBERT = 0.796 AMP-TURN 1 AMP-TURN = 1.25 GILBERT	AMPERE-TURN
FIELD INTENSITY OR MAGNETIZING FORCE	FORCE PER UNIT LENGTH OF FLUX PATH	H	$\frac{\text{AMPERE-TURN}}{\text{IN}}$	OERSTED $1\ \text{OERSTED} = \frac{1\ \text{GILBERT}}{\text{CM}}$	$\frac{\text{AMPERE-TURN}}{\text{M}}$

Figure 5-18

Comparison of magnetic units.

In the centimeter-gram-second, or cgs system, four new terms (maxwell, gauss, gilbert, and oersted) are introduced. The maxwell is equal to one line of force. The gauss is equal to 1 maxwell per square centimeter. The gilbert is equivalent to about 0.8 ampere-turns. Or stated another way, an ampere turn is equal to about 1.25 gilberts. Finally, the oersted is equal to 1 gilbert per centimeter.

In the meter-kilogram-second, or mks system, the unit of flux is the weber. The weber is equivalent to 10^8 or 100,000,000 lines of force. Flux density is expressed as webers per square meter. As with the English system, the mks unit of mmf is the ampere-turn. Finally, field intensity is expressed as ampere-turns per meter.

This table ignores permeability and reluctance because neither has a unit of measurement assigned to it in any of the three systems.

Programmed Review

22. When an electrical charge moves, a ____________ field is produced.

23. (magnetic) A moving magnetic field can produce electricity and a moving electrical charge produces a magnetic field. Thus, the common factor which links magnetism and electricity is ____________ .

24. (motion) A magnetic field is produced when current flows through a wire. You can determine the direction of the magnetic field around a wire by the ____________ magnetic field rule.

25. (left-hand) To apply this rule, you grasp the wire in your left hand with your ____________ pointing in the direction of current flow.

26. (thumb) Your ____________ now point in the same direction as the flux lines.

27. (fingers) The magnetic field produced around a conductor is relatively weak and although it has direction, it does not have north or south ____________ .

28. (poles) You can develop a stronger magnetic field which does have poles simply by winding the conductor in the form of a ____________ .

29. (coil) The center part of the coil is called the core. The magnetic lines of force are concentrated in this area. The lines of force enter at one end of the core and exit at the other. The end at which these lines enter the coil is called the ____________ pole.

30. (south) Because the coil has many of the characteristics of a magnet, the coil is called an ____________ .

31. (electromagnet) You can use another left-hand rule to determine the polarity of an electromagnet. To use this rule, grasp the coil in your left hand in such a way that your fingers point in the direction of ________________________________ .

32. (current flow) Your thumb is now pointing toward the ____________ ____________ of the coil.

33. (north pole) Some coils have an air core. However, you can greatly increase the flux by adding a core of some ferromagnetic material such as iron. The reason for this is the iron has a much higher value of ____________ than air.

34. (permeability) In addition to permeability, there are several other important magnetic quantities. One of the most important is measured in lines or kilolines. This quantity is defined as the total magnetic field or the total lines of force. It is called ____________ .

35. (flux) Another quantity refers to the amount of flux per unit of area. In the English system it is measured in lines per square inch. It is called flux ____________ .

36. (density) Magnetomotive force (mmf) is another of the basic magnetic quantities. It is defined as the force which produces the flux. In the English system, the unit of mmf is the __________–__________ .

37. (ampere-turn) Field intensity is the amount of mmf per unit of length of the coil. Its unit of measure is the __________ –__________ per inch.

38. (ampere-turn) A material which readily accepts flux lines has a high permeability. One which is reluctant to accept flux lines has a high ____________________.

39. (reluctance) Magnetic quantities are often compared to electrical quantities. The most common analogy compares current, voltage, and resistance to ____________, ____________, and ____________ respectively.

40. (flux, mmf, reluctance) Match the following English units with its cgs counterparts:

A. lines
B. lines/in^2
C. amp-turn
D. amp-turn/in

1. oersted
2. gilbert
3. maxwell
4. gauss

41. (A-3, B-4, C-2, D-1) Match the following English units with its mks counterparts:

A. lines
B. lines/in^2
C. amp-turn
D. amp-turn/in

1. weber/m^2
2. amp-turn
3. amp-turn/m
4. weber

42. (A-4, B-1, C-2, D-3) Match the following magnetic quantities with their English units:

A. flux
B. flux density
C. field intensity
D. magnetomotive force

1. lines/in^2
2. amp-turn
3. amp-turn/in
4. lines

43. (A-4, B-1, C-3, D-2).

INDUCTION

Induction is the effect of one body on another without any physical contact between them. For example, in an earlier unit, you saw that a charged body can *induce* a charge in another body simply by coming close to it. That is, a charge can be induced into a body without physical contact. This is possible because an electrostatic field surrounds every charged body. Thus, the field of a charged body can affect another body without the two bodies actually touching. This is an example of electrostatic induction.

Magnetic Induction

Another type of induction is called *magnetic induction*. Everyone knows that a magnet can affect objects at a distance. A strong magnet can cause a compass needle to deflect from a distance of several feet. Another power of the magnet is to induce a magnetic field in a previously unmagnetized object. For example, a magnet can induce a piece of iron to become a magnet.

Figure 5-19 shows a bar of soft iron close to a permanent magnet. Notice that part of the field of the magnet passes through the iron bar. Magnetic lines of force enter the left side of the iron and exit on the right. This magnetic field causes the magnetic domains in the iron to line up in one direction. Thus, the piece of iron itself becomes a magnet. The south pole must be on the left because this is the end where the flux lines enter the iron. The north pole is on the right because the flux lines exit at this point. Notice that the north pole of the permanent magnet is closest to the induced south pole of the iron bar. Because these opposite poles attract, the iron bar is attracted to the magnet. Therefore, attraction of a piece of iron by a permanent magnet is a natural result of magnetic induction.

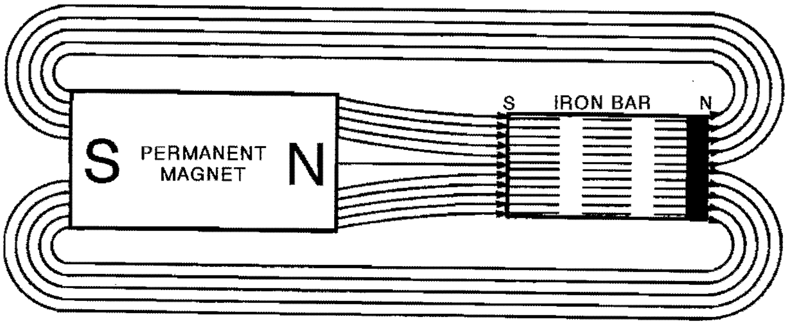

Figure 5-19
Magnetic induction.

When the piece of iron is removed from the magnetic field most of the magnetic domains return to random positions. However, a few of the domains remain aligned in the north-south direction shown in Figure 5-19. Thus, the iron bar retains a weak magnetic field even after you remove it from the influence of the permanent magnet. The magnetic field which remains in the iron bar is called *residual magnetism.* The ability of material to retain a magnetic field even after you remove the magnetizing force is called *retentivity.* Soft iron has a relatively low value of retentivity. Thus, it retains little residual magnetism. Steel has a somewhat higher value of retentivity. Therefore, its residual magnetism is also higher. Some materials such as alnico have a very high value of retentivity. In these materials, the residual magnetic field is almost as strong as the original magnetizing field.

Electromagnetic Induction

Electromagnetic induction is the action that causes electrons to flow in a conductor when the conductor moves across a magnetic field. Figure 5-20 illustrates this action. When conductor moves up through the magnetic field, the free electrons are pushed to the right end of the conductor. This causes an excess of electrons at the right end of the conductor and a deficiency of electrons at the other end. This results in a potential difference between the two ends of the conductor. However, this potential difference exists only while conductor is cuts the flux lines of the magnet. When the conductor moves out of the magnetic field, the electrons return to their original positions and the potential difference disappears. The potential difference also disappears if the conductor stops in the magnetic field. Thus, the conductor must move with respect to the flux lines before a potential difference is developed.

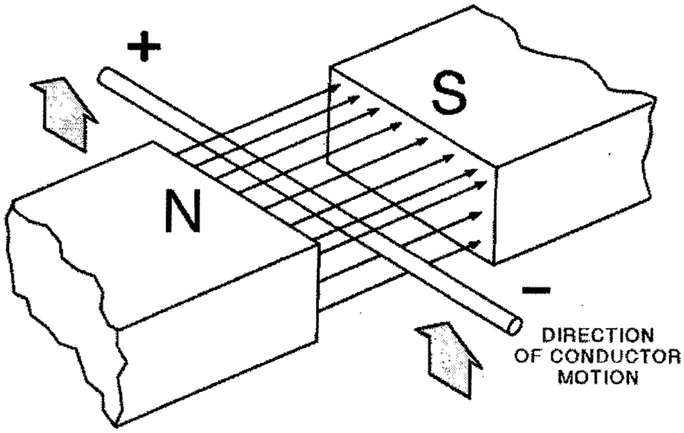

Figure 5-20
Electromagnetic induction.

Motion is essential to electromagnetic induction. Some outside force must be applied to cause the conductor to move through the magnetic field. This mechanical force is converted to an electromotive force (emf) by electromagnetic induction. An emf is induced into the conductor. The potential difference across the conductor is called an *induced emf* or an *induced voltage*.

The following four factors determine the amount of emf induced into the conductor:

1. The strength of the magnetic field.
2. The speed of the conductor with respect to the field.
3. The angle at which the conductor cuts the field.
4. The length of the conductor in the field.

The stronger the magnetic field, the greater the induced emf. Also, the faster the conductor moves with respect to the field, the greater the induced voltage. Relative motion between the conductor and the field can be produced by moving the conductor, by moving the field, or by moving both. The angle at which the conductor cuts the field is also important. Maximum voltage is induced when the conductor moves at right angles to the field as shown in Figure 5-20. Less voltage is induced when the angle between the lines of flux and the direction of motion of the conductor is less than 90°. In fact, if the conductor is moved parallel to the lines of flux as shown in Figure 5-21, no emf is induced at all. The fourth factor is the length of the conductor in the field. The longer the conductor, the greater the induced emf.

All four of these factors are a natural consequence of a basic law of electromagnetic induction. This law is called Faraday's Law and it states:

> "The voltage induced in the conductor is directly proportional to the rate at which the conductor cuts the magnetic lines of force."

In other words, the more flux lines per second which are cut, the higher the induced emf will be

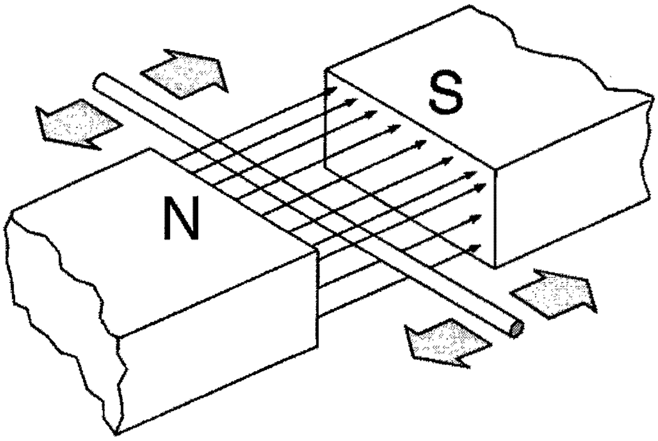

Figure 5-21
No voltage is induced when the conductor moves parallel to the flux lines.

You can use another left-hand rule to determine the polarity of the induced emf. This one is called the *left-hand rule for generators* and is illustrated in Figure 5-22. It involves your thumb and the first two fingers of your left hand. Point your thumb in the same direction that the conductor is moving, and point your index or forefinger in the same direction as the flux lines. Now, point your middle finger straight out from your palm at a right angle to your index finger. Your middle finger now points to the negative end of the conductor. This is the direction in which current flows if you connect an external circuit across the two ends of the conductor.

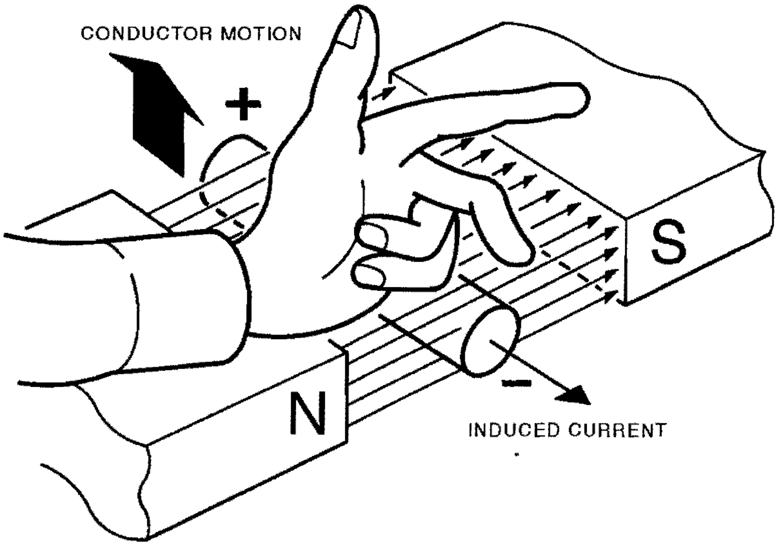

Figure 5-22
Left-hand rule for generators.

The AC Generator

Electromagnetic induction is important because it supplies virtually all of the electrical power used in the world today. It is the most efficient way known of producing electricity. Figure 5-23 shows a very basic electric generator. This device uses electromagnetic induction to convert mechanical energy into electric energy. Mechanical energy is required to establish relative motion between the magnetic field and the conductor. Either the magnet or the conductor can be rotated. For this explanation, assume the conductor rotates in the counterclockwise direction. Notice that the conductor is shaped like a loop and is called an armature. When the loop or armature rotates, one half moves up through the field near the south pole while the other half moves down through the field near the north pole.

If you apply the left hand generator rule to the side of the loop nearest the south pole, you find that the polarity of the induced voltage is negative at point A and positive at point B. When you apply the same rule to the conductor near the north pole, you find that the induced voltage is negative at point C and positive at point D. Notice that the two induced voltages are series-aiding. A meter connected between points E and F will indicate the sum of the two induced voltages.

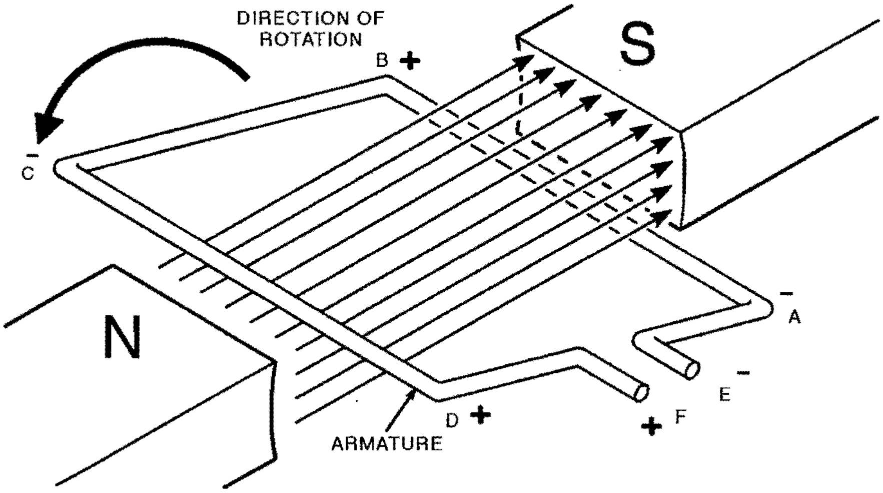

Figure 5-23
The AC generator.

Figure 5-24A shows the nature of the voltage which is induced into the armature. To see how this voltage is produced, you must follow the armature through one complete revolution. In each case, you will consider the voltage at point A with respect to point B. Figure 5-24B shows the armature at 90° increments. At 0°, the sides of the armature are moving parallel to the lines of flux. Thus, there is no induced voltage at this time. However, as the armature rotates, the loop begins to cut the lines of flux and a voltage is induced. Point A becomes positive with respect to point B. The voltage begins to rise and reaches its highest value at 90° of rotation. The voltage is maximum at this point because the armature is cutting the flux at a right angle. Thus, it cuts the maximum number of lines at this point. Once past 90°, the voltage begins to decrease because fewer lines per second are being cut. At 180°, the induced voltage is again zero because the armature is moving parallel to the lines. As the loop passes 180° and starts to cut the lines again, a voltage is once again induced. However, this time point A becomes negative with respect to point B. You can apply the left-hand generator rule to prove this. The maximum negative voltage is produced at 270° when the armature once again cuts the lines at right angles. As the armature heads back toward its starting point, the voltage begins to decrease back toward 0. At 360°, the armature is back where it started and the induced voltage is again zero.

The voltage shown in Figure 5-24A is called a *sine-wave*. One cycle of the sine-wave is produced for each revolution of the armature. If a load is connected across the armature between points A and B, current will flow through the load. For the first half cycle, current flows from point B through the load to point A. However, during the next half cycle, current flows from point A, through the load in the opposite direction to point B. Thus, during each cycle, the current reverses direction - flowing in one direction half of the time and flowing in the opposite direction the other half of the time. This is called alternating current and is abbreviated ac.

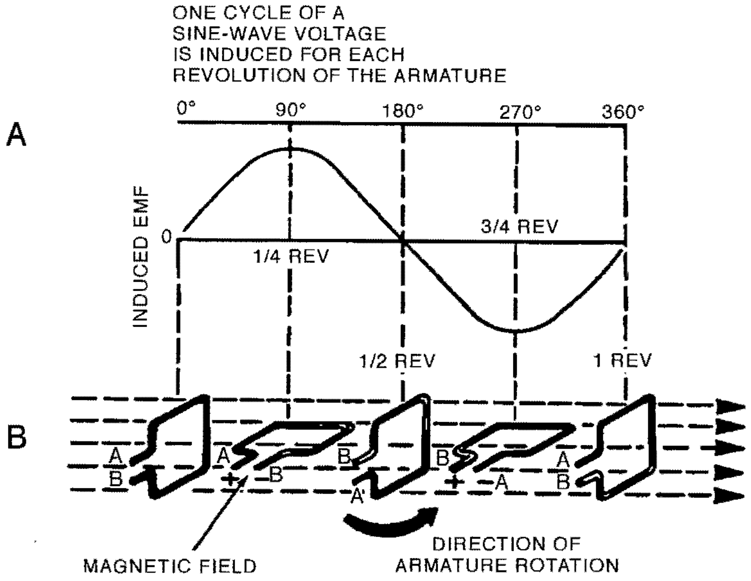

Figure 5-24

Generating a sine-wave.

The voltages supplied to our homes, offices, and factories are AC voltages. The armature of the generator at the plant which provides our power rotates 60 times each second. Thus, the voltage supplied by these power stations goes through 60 cycles like the one shown in Figure 5-24A each second. Most of the appliances in your home require 115 volts at 60 cycles.

An AC generator is often called an *alternator* because it produces alternating current. The simple machine shown here would not produce useful power because the armature consists of only one turn of wire. In a practical alternator, hundreds of turns are wound into an armature which can produce considerable power.

The DC Generator

The AC generator or alternator can be converted to a DC generator. A device called a *commutator* converts the AC voltage produced by the rotating loop into a DC voltage. Figure 5-25A shows how the commutator connects to the loop. The commutator is a cylinder shaped conductor. Two insulators are used to separate one half of the cylinder from the other half. Opposite sides of the loop are permanently connected to the opposite sides of the commutator. Thus, the commutator rotates with the loop. *Brushes* make contact with the rotating commutator. The brushes are stationary and rest against opposite sides of the commutator. The brushes are made of a conducting material so that the emf produced by the loop is transferred to the brushes. In turn, wires connect to the brushes so that the emf can be transferred to an external circuit.

The complete DC generator is shown in Figure 5-25B. Notice that it has four basic parts: a magnet to produce the magnetic field, a loop which produces the emf, a commutator which converts the induced emf to a DC voltage, and the brushes which transfer the DC voltage to an external circuit.

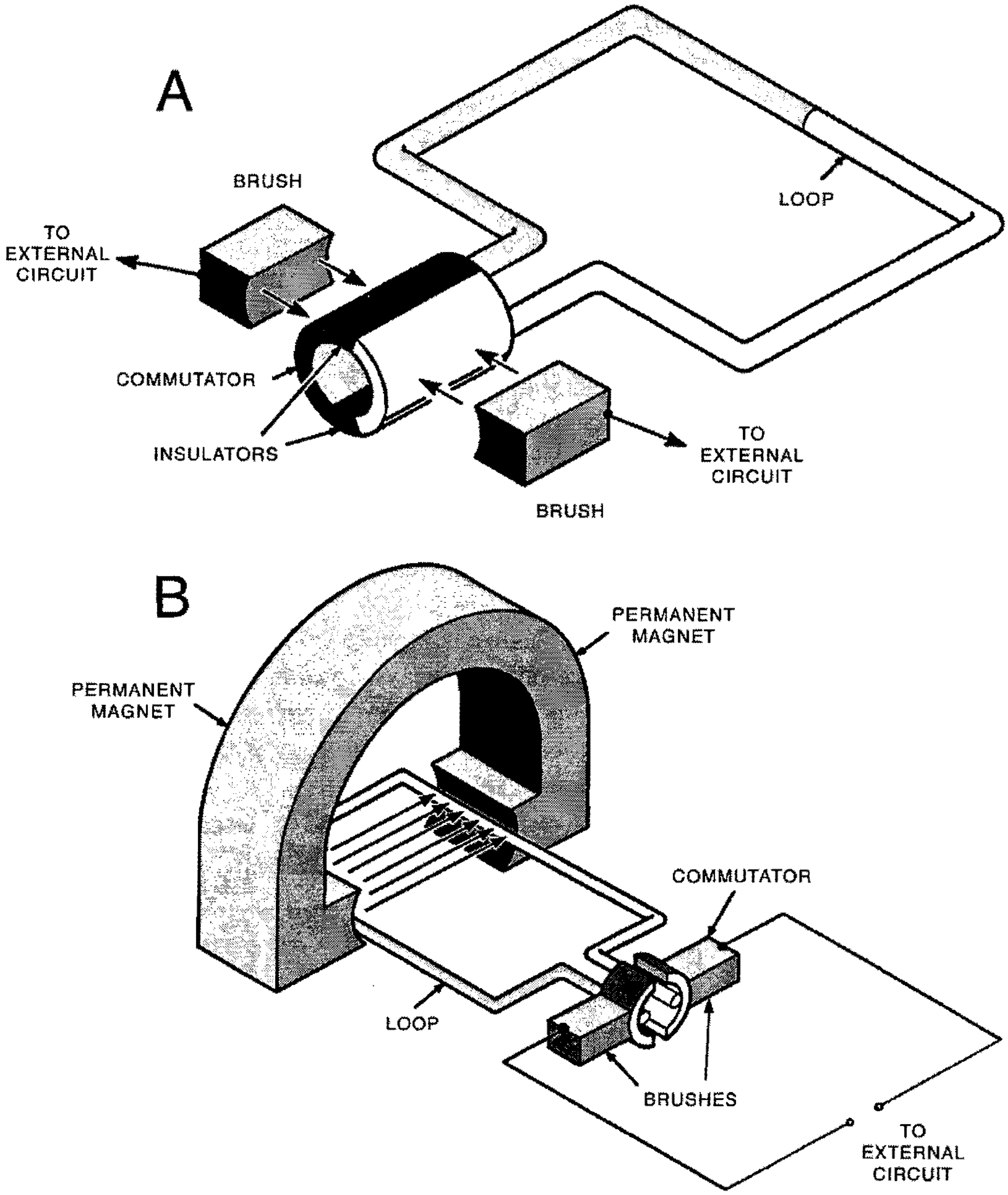
A
BRUSH
TO EXTERNAL CIRCUIT
LOOP
COMMUTATOR
INSULATORS
TO EXTERNAL CIRCUIT
BRUSH
B
PERMANENT MAGNET
PERMANENT MAGNET
COMMUTATOR
LOOP
BRUSHES
TO EXTERNAL CIRCUIT

Figure 5-25
The DC generator.

Figure 5-26 illustrates the operation of the DC generator. At 0°, 180°, and 360°, the sides of the loop are moving parallel to the flux lines and 0 volts is produced. This same situation existed with the AC generator. At 90° and 270°, the sides of the loop cut the flux lines at right angles. Thus, maximum voltage is produced. However, unlike the alternator, the voltage is positive at point A with respect to point B at both 90° and 270°. Here's see why.

Since the brushes are stationary and the commutator is rotating, each brush alternately connects to opposite sides of the loop. When the magnetic field is in the direction shown, the side of the loop which is moving up through the field produces a negative voltage at the commutator. Also, the side of the loop moving down through the field produces a positive voltage at the commutator. Notice that the brush on the right is always connected to the side of the loop which is moving up through the field. Consequently, this brush is negative. On the other hand, the brush on the left is always connected to the side of the loop which moves down through the field. Consequently, this brush is positive. Thus, if an external circuit is connected across A and B, current always flows in the same direction, i.e., from B to A.

The nature of the induced emf is shown in Figure 5-26B. This is called a pulsating DC voltage – *DC* because the current always flows in the same direction and *pulsating* because the level fluctuates. A pulsating DC voltage like this one has little use in this form. However, as you will see in a future unit, this type of voltage can be smoothed out to form a constant DC voltage.

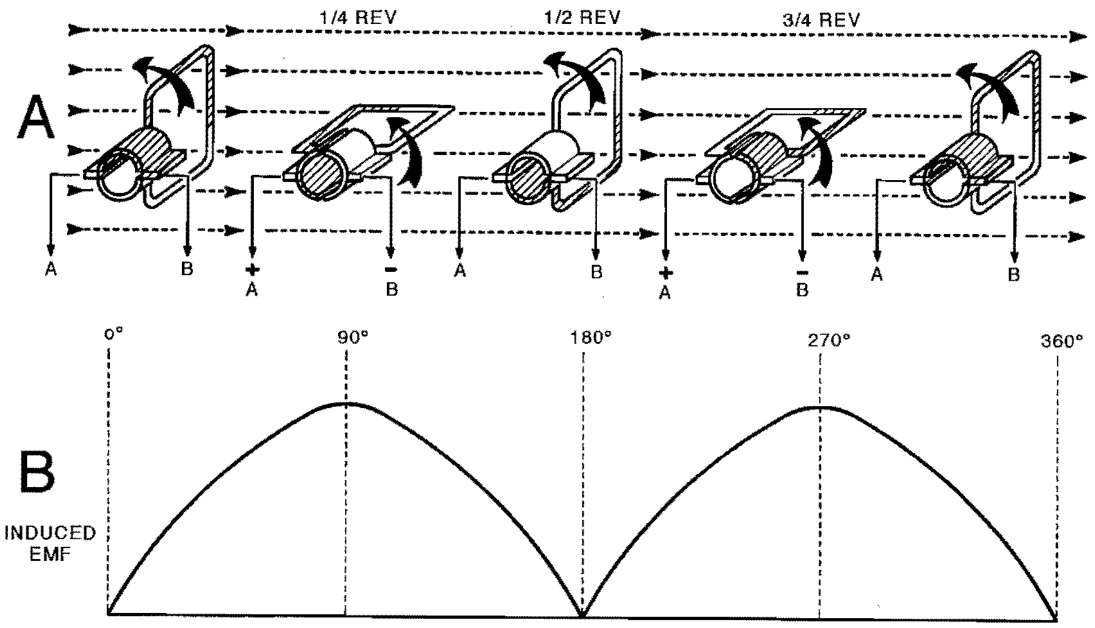

Figure 5-26

Operation of a DC generator.

Programmed Review

44. The effect of one body changing the nature of another body in some way without any physical contact between them is called ____________ .

45. (induction) When a charged object is brought close to a neutral object, the neutral object develops a charge of its own. This is called charging by electrostatic ________________ .

46. (induction) In much the same way, a permanent magnet can induce a magnetic field in a previously unmagnetized object. This is called ________________ induction.

47. (magnetic) An iron bar retains a weak magnetic field even after you remove it from the influence of a permanent magnet. The magnetic field which remains after you remove the magnetizing force is called ____________ magnetism.

48. (residual) The ability of a material to retain a magnetic field after you remove the magnetizing force is called ____________ .

49. (retentivity) The action that causes electrons to move in a conductor when the conductor moves across a magnetic field is called ____________ induction.

50. (electromagnetic) The amount of induced emf is determined by four factors. The stronger the magnetic field, the _____________ the induced emf.
stronger/weaker

51. (stronger) The faster the relative motion, the _____________ the induced emf.
stronger/weaker

52. (stronger) The longer the conductor in the field, the ____________ the induced emf. stronger/weaker

53. (stronger) Finally, the angle at which the conductor moves through the magnetic field is important. The induced emf is maximum when the conductor cuts the magnetic field at a ____________ angle.

54. (90° or right) You can use the left-hand rule for ____________ to determine the polarity of the induced emf.

55. (generators) To use this rule, you point the ____________ of your left-hand in the same direction that the conductor is moving.

56. (thumb) You point your ____________ finger in the same direction as the flux lines.

57. (index or fore) If you now point your middle finger straight out from your palm at a right angle to your index finger, it point at the ____________ end of the conductor. negative/positive

58. (negative) A device which uses electromagnetic induction to convert mechanical energy to electrical energy is called a ____________ .

59. (generator) An AC generator is called an alternator. In its simplest form, it consists of a loop of wire that rotates in a magnetic field. It produces an ____________ current emf.

60. (alternating) One cycle of this alternating current produces a voltage waveform called a ____________ wave.

61. (sine) A DC generator also has a rotating loop and a magnetic field. However, a ______________ converts the AC voltage to a pulsating DC voltage.

62. (commutator).

MAGNETIC AND ELECTROMAGNETIC APPLICATIONS

You have already seen two important applications of electromagnetism – the alternator and the DC generator. It would be difficult to list all of the other applications of magnetic and electromagnetic devices. However, you can examine the operation of some of the more common applications.

Relay

A relay is one of the simplest electromagnetic devices. It is also one of the most useful. Figure 5-27 shows how a relay operates. When you close the switch, current flows from the battery through the relay coil. The current develops a magnetic field in the core which attracts the armature, pulling it down. This causes the two contacts to close to connects the generator to the load.

When you open the switch, the current through the relay coil stops. This allows the magnetic field to collapse. The spring pulls the armature back up to open the contacts and disconnect the generator from the load.

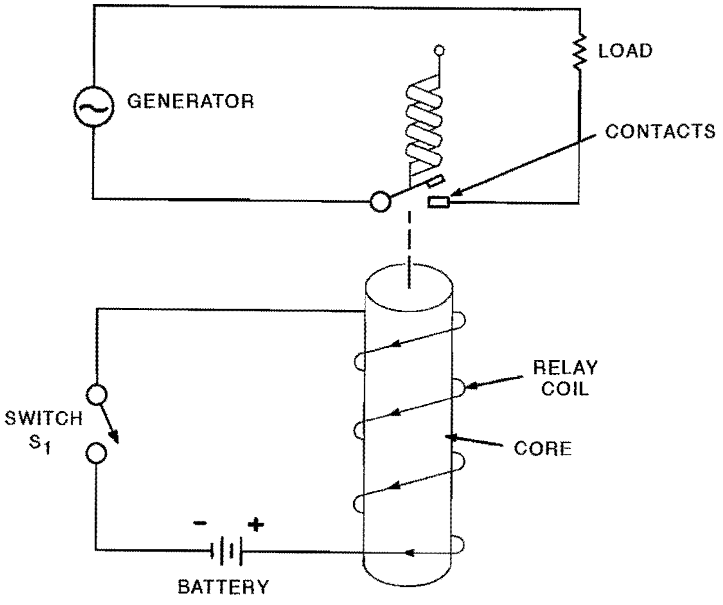

Figure 5-27
A relay.

A relay is used when it is desirable to have one circuit control another. Notice that in Figure 5-27 there are two complete and separate circuits. Because the relay circuit is electrically isolated from the generator circuit, a relay can be used to open and close high-voltage or high-current circuits with relatively little voltage and current in the coil circuit. It is also useful for remote control where the switch is located at one point and the other circuit components are located at a distance. Also, a relay with several contact arms can open and close several circuits at once.

An interesting application of the relay is the door bell shown in Figure 5-28. When you close the switch, current flows from the negative side of the battery through the switch, the breaker contacts, the two relay coils, and back to the positive side of the battery. The current flow through the relays sets up a magnetic field which attracts the soft-iron armature and pulls it down. This pulls the hammer down and causes it to strike the bell. The lower breaker contact is attached to the armature. Consequently, when the coils energize, it breaks the current path for the coil. Thus, the relay de-energizes and releases the armature. The spring pulls the armature and the hammer upward. This closes the breaker contacts and once again completes the path for current flow through the relays. The operation repeats itself many times each second. Thus the bell is rings as long as the circuit is energized.

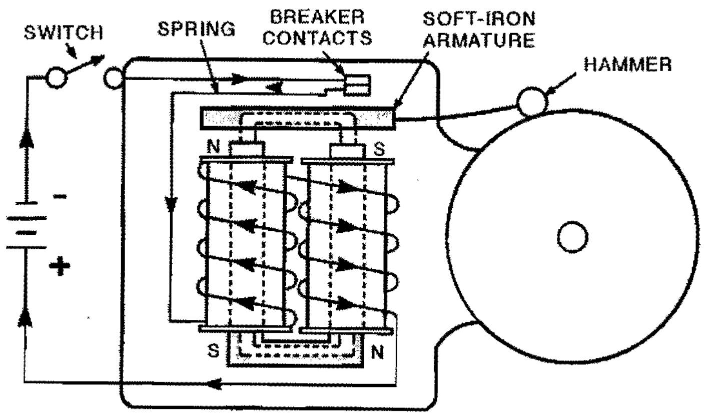

Figure 5-28
The door bell.

Reed Switch and Relay

Figure 5-29A shows a magnetic reed switch. It consists of two contacts in a sealed glass container. The contacts are made of a ferromagnetic material and are normally open. However, when you place a magnet next to the reed switch as shown in Figure 5-29B, the contacts close. This happens because a magnetic field is induced into each contact by the flux lines from the magnet. Thus, each contact becomes a tiny magnet that has the polarity shown. At the point where the two contacts are closest, opposite poles exist. These poles are attracted to each other which closes the contacts. The reed switch allows you to turn a current on or off by changing the position of a permanent magnet. You will learn about a practical application of this device later.

Figure 5-29C shows that you can also control the contacts with a field from an electromagnet. When the electromagnet is wound directly on the reed switch, the device is called a reed relay.

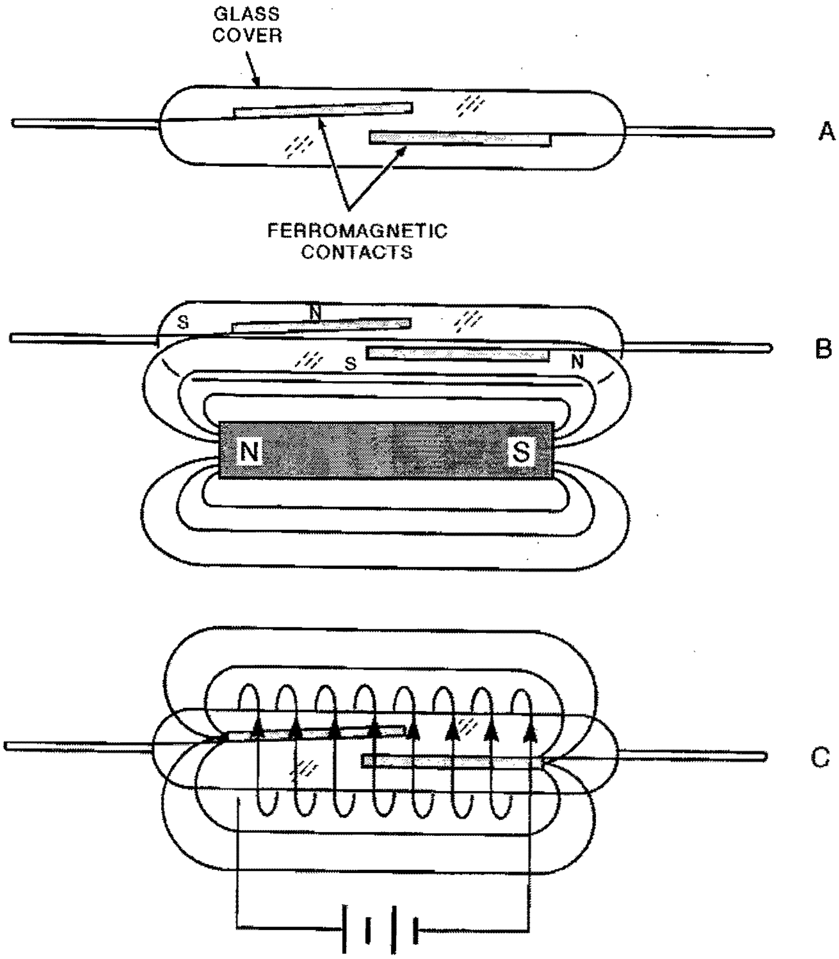

Figure 5-29
Reed switch and reed relay.

Record Pickup

Electromagnetic principles are used in many types of recording and playback equipment. The pickup cartridge that was used in the tone arm of many record players were electromagnetic devices. Figure 5-30 shows the construction of a cartridge called a moving-coil or dynamic pickup. Here, a magnetic field is produced by the permanent magnet. A tiny coil is placed in this magnetic field. The core on which the coil is wound is attached to the stylus or needle. The coil is held in place by a flexible grommet. As the needle slips down the spiral groove on the record, it vibrates in response to the variations in the groove. These variations in the groove correspond to the audio tones recorded there. Thus, the needle vibrates at the same rate as the audio tones. Because the coil is connected to the needle, it also vibrates at this rate. The tiny movements of the coil in the magnetic field cause a minute emf to be induced into the coil. The induced emf also varies at the audio rate. This emf can be amplified and used to drive a loudspeaker so that the original audio tone is reproduced.

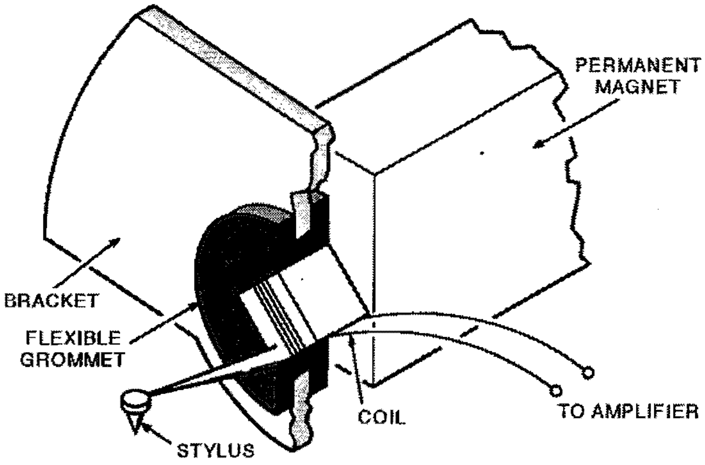

Figure 5-30
Simplified diagram of a magnetic-pickup cartridge.

Loudspeaker

Loudspeakers are used in all types of audio equipment. Most loudspeakers use a moving coil and a permanent magnet. A cutaway diagram of a loudspeaker is shown in Figure 5-31. A permanent magnet establishes a strong stationary magnetic field. A coil which is free to move is placed in this magnetic field. A current which varies at an audio rate then passes through the coil. The varying current establishes a varying magnetic field around the coil. The varying magnetic field of the coil is alternately attracted and repelled by the stationary field of the permanent magnet. Thus, the coil moves back and forth at the same rate as the varying current. The moving coil is attached to a large cone or diaphragm. As the coil vibrates, the cone also vibrates setting the air around the cone in motion at the same rate. This reproduces the original sound.

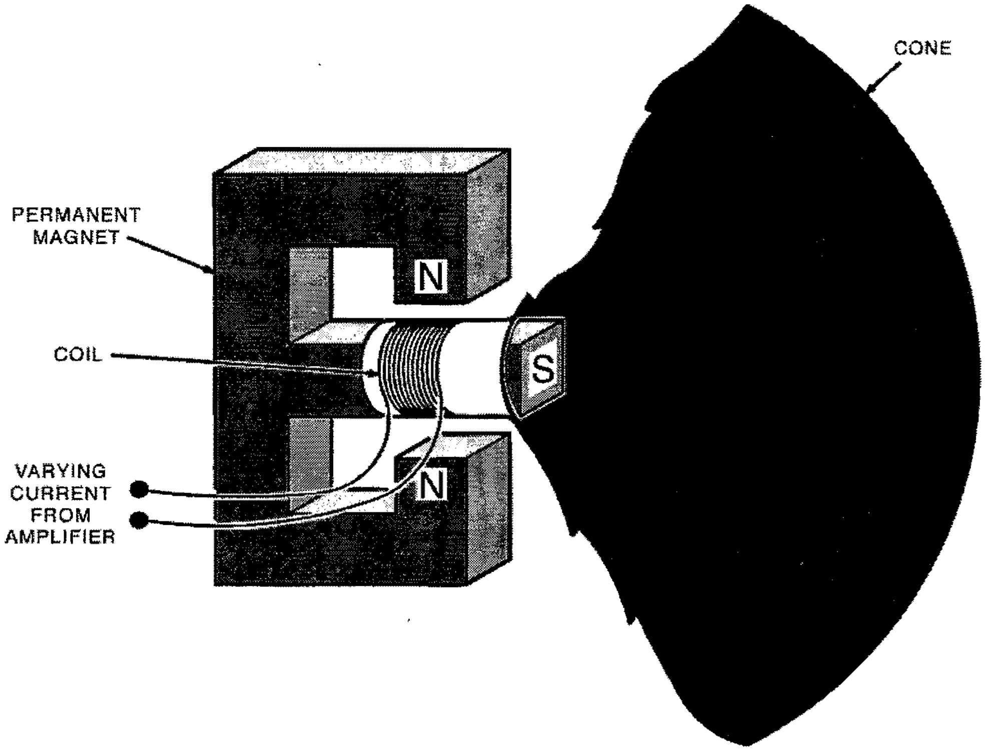

Figure 5-31
The loudspeaker.

Magnetic Tape

The tape recorder uses electromagnetic principles to record electronic signals on magnetic tape. The device which actually "writes" the signal on the tape and later "reads" it back is called a record-playback head. It is nothing more than a coil with a ferromagnetic core. Figure 5-32A illustrates the operation in the record mode.

Notice that a tiny air gap exists between the two ends of the core. When current is applied to the coil, a magnetic field is concentrated in this gap. A length of magnetic tape is pulled past the air gap. The plastic tape is covered with a ferromagnetic substance such as iron oxide. The magnetic field that surrounds the air gap penetrates the tape and magnetizes it at this point. If the current applied to the coil varies at an audio rate, the magnetic field across the air gap varies at the same rate. Consequently, the magnetic pattern that is "written" onto the tape corresponds to the original audio signal.

To play back the tones recorded on the tape, the process reverses as shown in Figure 5-32B. The tape is pulled past the air gap so that the core is subjected to the magnetic patterns on the tape. The changing magnetic field induces a tiny emf into the coil windings. When this emf is amplified and applied to a loudspeaker, the original audio tones are reproduced.

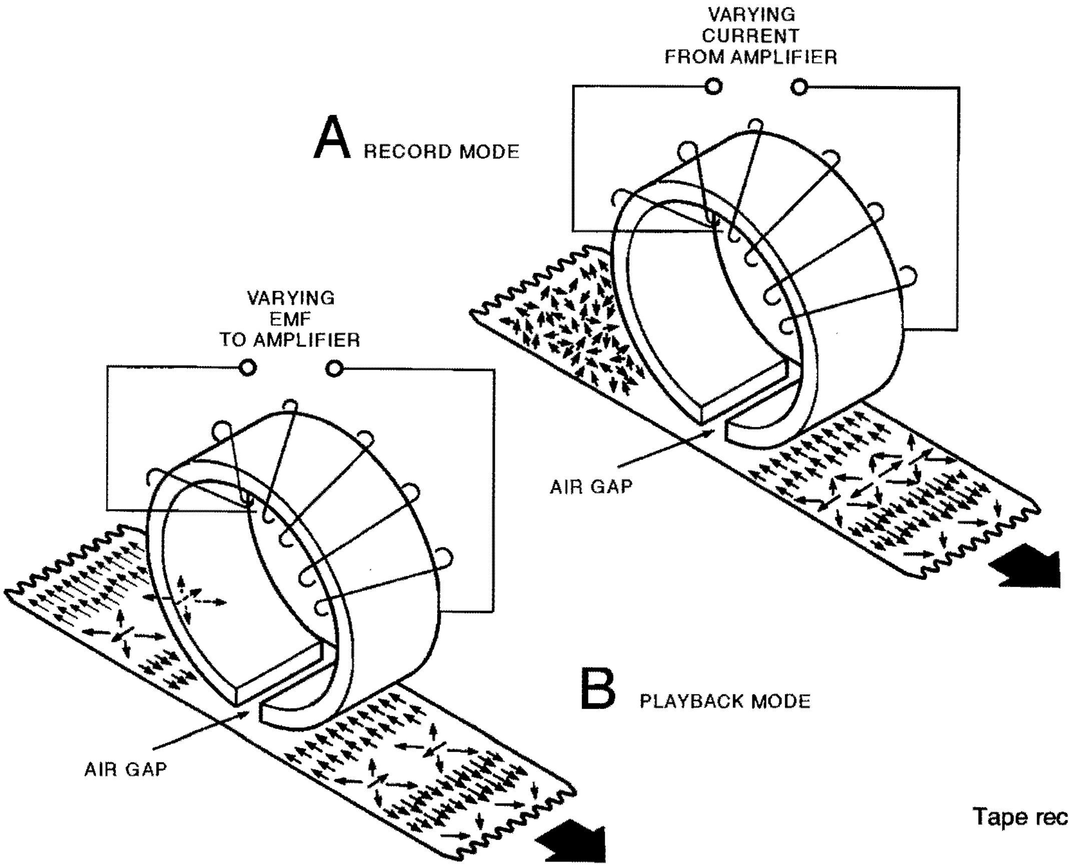

Figure 5-32
Tape record and playback head.

DC Motor

Earlier you saw that a generator converts mechanical energy to electrical energy. A motor does just the opposite; it converts electrical energy to mechanical energy. Figure 5-33A illustrates the principle which makes this possible. Here, a current carrying conductor is shown in a magnetic field. This is not an induced current; it flows because the conductor is connected across a battery. The current causes a magnetic field to be developed around the conductor in the direction shown. You can use the left-hand rule for conductors discussed earlier to verify this. The magnetic field around the conductor interacts with the field of the permanent magnet. Notice that on one side of the wire, the two magnetic fields have the same direction and they add to produce a strong magnetic field. On the other side of the conductor the two magnetic fields have opposite directions. Thus, they tend to cancel and leave a weak resultant field at this point. As you can see, the flux lines are much more numerous on one side of the conductor than on the other. Thus, on one side, the lines bend and are forced very close together. These lines have a natural tendency to straighten and move further apart. However, the only way they can do this is by pushing the conductor out of the way. Thus, a force is developed which will push the conductor in the direction shown.

There is a rule for determining the direction that the wire will move. It is called the *right-hand motor rule*, and is illustrated in Figure 5-33B . With your right-hand (not the left), point your index finger in the direction of the field of the permanent magnet. Point your middle finger in the direction of current flow through the conductor and at a right angle to your index finger. Point your thumb straight up and at a right angle to both your index and middle fingers. Your thumb now points in the direction that the conductor will move. You can apply this rule to see how a simple DC motor operates.

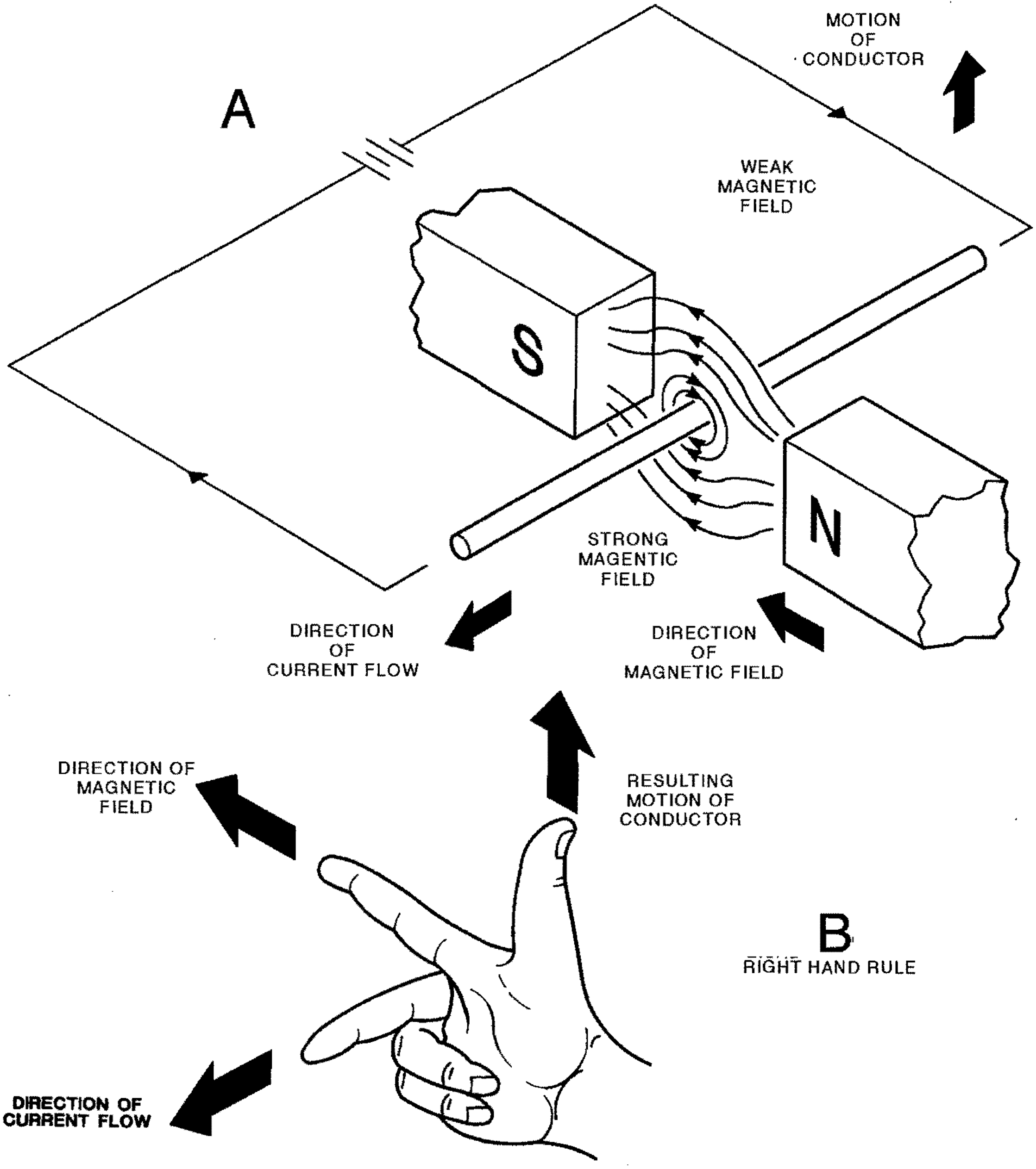
MOTION
OF
CONDUCTOR
A
WEAK
MAGNETIC
FIELD
S
N
STRONG
MAGENTIC
FIELD
DIRECTION
OF
CURRENT FLOW
DIRECTION
OF
MAGNETIC FIELD
DIRECTION OF
MAGNETIC
FIELD
RESULTING
MOTION OF
CONDUCTOR
B
RIGHT HAND RULE
DIRECTION OF
CURRENT FLOW

Figure 5-33
Rules for motor action.

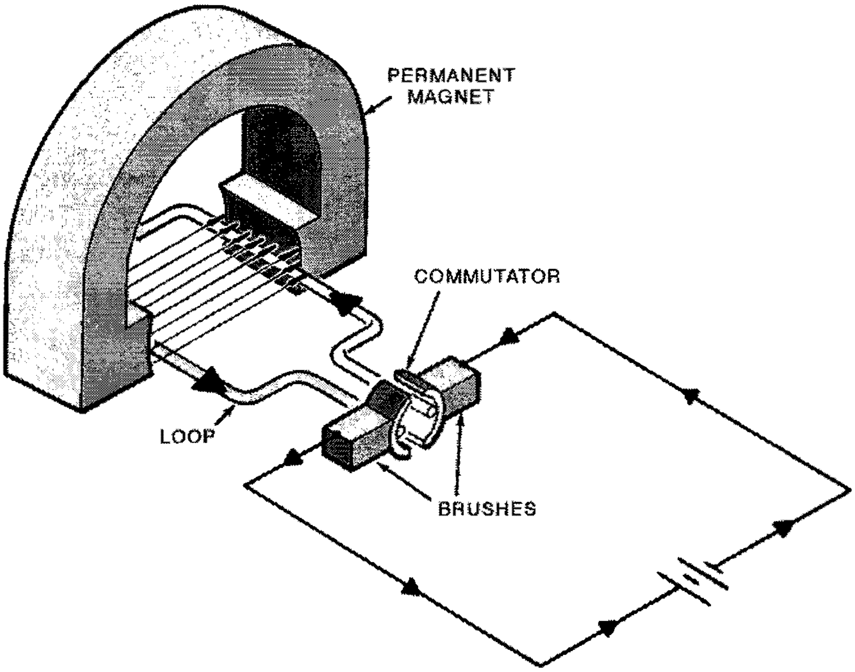

Figure 5-34
The DC motor.

A simplified diagram of the DC motor is shown in Figure 5-34. Notice the similarity to the DC generator described earlier. However, there are two important differences. With the generator, the loop was turned by an outside mechanical force. Here, the loop turns due to the motor action just described. In the generator, a DC voltage was produced at the brushes. Here, an external DC voltage from a battery is applied to the brushes.

Current flows through the loop as indicated by the arrows. If you apply the right-hand motor rule to the side of the loop near the south pole of the magnet, you find that the conductor tends to move up. If you apply the same rule to the side near the north pole, you° find that this side tends to move down. Thus, the loop rotates in a counterclockwise direction. After one half cycle of revolution, the two sides reverse positions. Nevertheless, current still flows in the same direction through the side closest to the south pole. Whichever side of the loop appears at this point, the resulting motion is always up. The upward force at the south pole and the downward force at the north pole causes the loop to constantly rotate.

The simple motor shown here is not practical because a single loop of wire is used as an armature. Real motors use hundreds of turns of wire to develope a very strong twisting motion, or torque.

Meter

The same motor action described above is used in the moving-coil meter movement. Figure 5-35 shows a simplified diagram of this device. Like the motor, it has an armature which is free to revolve in the field of a permanent magnet. However, in the meter movement, one or more springs restrict the motion. When current flows through the coil, it establishes a magnetic field whose strength is directly proportional to the current. The motor action causes the coil to rotate. However, the restraining springs prevent the coil from rotating more than about 90°. A pointer is attached to the coil. As the coil rotates, it moves the pointer in front of a scale. As more current flows, the coil will rotate further and the pointer will move further up the scale. The scale reading is directly proportional to the amount of current that flows through the coil. Therefore, the scale can be marked off in amperes, milliamperes, or even microamperes. Most analog ammeters, voltmeters, and ohmmeters use this type of meter movement.

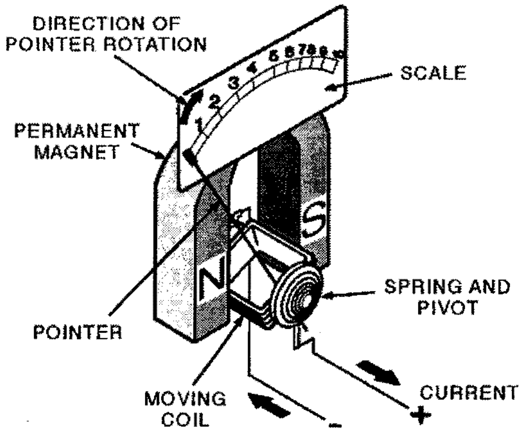

Figure 5-35
The moving-coil meter movement.

Computer Memories

Computers use a variety of electromagnetic devices to store information. At the start, one of the most used storage techniques was magnetic cores. These were tiny little doughnut-shaped pieces of ferrite material which could be magnetized in either of two directions. As shown in Figure 5-36, wires were strung through the holes in the cores. When current is applied to these wires in the appropriate direction, the cores could be magnetized in a certain pattern. A clockwise magnetic field can arbitrarily be called 1 while a counterclockwise field can be called 0. The cores in Figure 5-36 have the pattern 0101. Patterns of 1's and 0's can be used to represent numbers, letters of the alphabet, and punctuation marks. For example, one popular computer code uses seven digit patterns. The letter A is represented by 1000001; the number 6 by 0110110; and the question mark (?) by 01111111. Thus, if you were willing to use enough cores, you could use seven digit patterns of 1's and 0's to store the entire contents of this course in a core memory. Although not used much anymore, they did have the advantage of retaining their memory during a power loss.

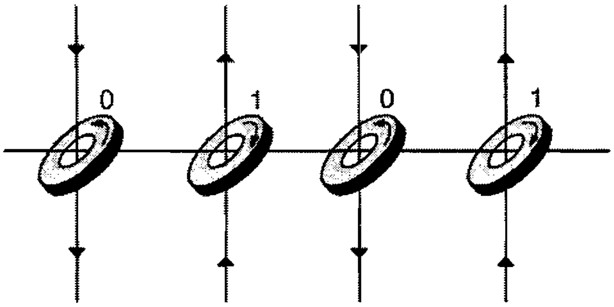

Figure 5-36
Four cores of a computer memory.

Magnetic Deflection of Electron Beams

You have seen that a current-carrying conductor is deflected (moved) by a magnetic field. However, it is not the conductor which is deflected but the electrons traveling through the conductor. Since the electrons are confined to the wire, the conductor also moves.

In some cases, streams of electrons are not confined to a wire but travel through empty space. Such a beam can be deflected in the same way that a current-carrying conductor is deflected. There are many practical applications of this principle. The most familiar is the TV picture tube like the one shown in Figure 5-37. A device called an electron gun produces a narrow beam of electrons which is fired at the TV screen. Wherever the beam hits the phosphor screen, light is given off. By moving the beam over the entire surface of the screen while varying its intensity, a picture can be drawn.

Two magnetic fields are used to deflect the beam. One moves the beam back and forth across the screen over 15,000 times each second. Another moves the beam up and down the screen 30 times each second. The result is that 30 complete pictures which consist of about 500 lines each are drawn each second.

The horizontal deflection coils are shown in Figure 5-37. When current flows in one direction through these coils, a magnetic field that has the direction shown is produced. You can use the right-hand motor rule to see that this field deflects the beam toward point A. If you reverse the direction of the field, the beam deflects toward point B. To deflect the beam in a vertical direction, vertical deflection coils are placed on the sides of the picture tube. This principle is used in radar sets and TV cameras as well as TV receivers.

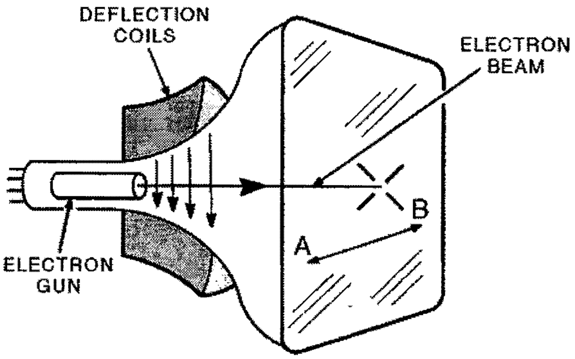

Figure 5-37
Magnetic deflection of the electron beam in a TV picture tube.

Programmed Review

63. The relay produces a magnetic field which closes the contacts of a switch. The relay shown in Figure 5-2 7 produces a __________ magnetic pole at the top of the coil.
north/south

64. (north) A doorbell has a relay which receives current through its own switch contacts. Thus, as soon as the relay is energized, current is __________________ the relay.
applied to/removed from

65. (removed from) In the moving-coil record-player pickup, a voltage is developed by vibrating a moving-coil in a stationary ____________ ____________ .

66. (magnetic field) In the loudspeaker, a varying current is applied to a ____________ ____________ to vibrate a speaker cone.

67. (moving-coil) The record-playback head that is used in tape recording uses a varying current which establishes a varying magnetic field. This field aligns the magnetic ____________ on the tape in certain patterns.

68. (domains) A rule is used to determine the direction that a current-carrying conductor will move when the conductor is placed in a magnetic field. The rule is called the ____________ ____________ rule for motors.

69. (right-hand) To use this rule, you hold your forefinger, middle finger and thumb at right angles. Your forefinger should point in the direction of the magnetic field, while your middle finger should point in the direction of current flow through the conductor. Your ____________ now points in the direction that the conductor will move.

70. (thumb) This same rule applies to other devices as well as the motor. A ____________ uses this technique to deflect a pointer in front of a scale.

71. (meter) The TV receiver uses this same technique to deflect an ____________ ____________ back and forth across the face of the picture tube.

72. (electron beam) In some older computer memories, small magnetic doughnut shaped devices called ____________ are used to store information.

73. (cores)

EXPERIMENT 13

Electromagnetism

OBJECTIVES: *To verify the left-hand rule for conductors.*

To verify the left-hand rule for coils.

To prove that the strength of a magnetic field is directly proportional to the current flow through the coil.

Introduction

In this first of two experiments pertaining to magnetism, you will concentrate on the fundamental rules and concepts associated with electromagnetism. In many ways, the practical relationship between electricity and magnetism may be summarized in the three objectives of this experiment, that is, the left-hand rule for conductors, the left-hand rule for coils, and the direct relationship between the amount of current flow and the strength of its magnetic field. By keeping in mind that electron current flows from negative to positive, you will be able to see the simplicity and close relationship between the left-hand rules. Both relate the direction of current to the direction of magnetic force in a wire. Feel free to review these rules as necessary in relation to this experiment. The third objective simply states that the greater the current, the stronger the magnetic field.

Material Required

1 — Heathkit Analog Trainer
1 — Multimeter with test leads
1 — Compass (#406-4)
1 — 100 Ω, 5%, 2-watt resistor (brown-black-brown-gold)
1 — 470 Ω, 5%, 1/2-watt resistor (yellow-violet-brown-gold)
1 — 1 kΩ, 5%, 1/2-watt resistor (brown-black-red-gold)
1 — Slide switch (#60-2) with wires attached
#22 copper wire

Procedure

1. Switch the Trainer ON and adjust the + voltage control for +10 V between the POS and GND terminals. Adjust the – voltage control for –10 V between the NEG and GND terminals. NOTE: If you use an analog meter, be sure to pay attention to meter polarity before you measure NEG to GND.

2. Connect the circuit shown in Figure 5-38. Set the slide switch to the OFF (open) position so that no current flows.

3. Use Ohm's Law to determine the current that will flow through wire A when you close the slide switch. The current will be ___________ mA.

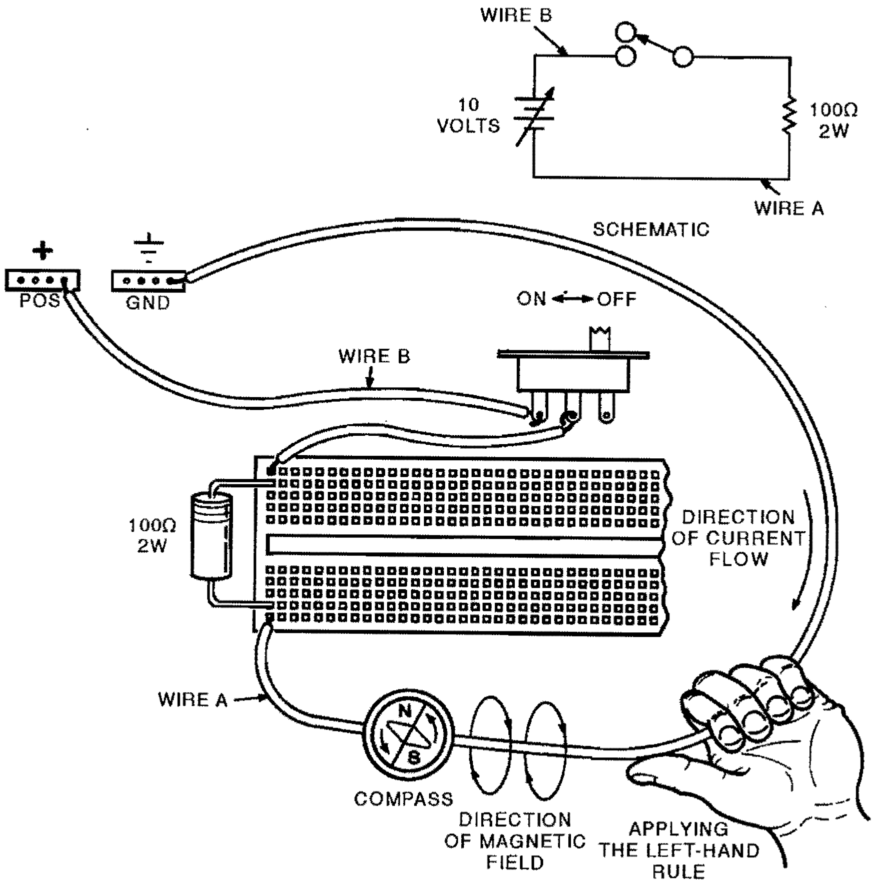
WIRE B
10
VOLTS
100Ω
2W
WIRE A
SCHEMATIC
+
POS
GND
ON ⟷ OFF
WIRE B
100Ω
2W
DIRECTION
OF CURRENT
FLOW
WIRE A
N
S
COMPASS
DIRECTION
OF MAGNETIC
FIELD
APPLYING
THE LEFT-HAND
RULE

Figure 5-38
Performing Oersted's experiment.

4. Find the compass that is provided with this course. When you use the compass, it may be necessary to tilt it slightly so that the needle is balanced and swings freely without touching the bottom of the holder.

5. Determine which end of the compass needle is the north pole. That is, determine which end of the compass needle points north. The compass is quite sensitive and you should not use it close to metal objects or magnetic fields. Otherwise, it will not align itself in a north-south direction.

6. Set the compass on top of wire A. Orient the Trainer and compass so that the north pole of the compass points toward the left. Orient wire A so that it is in line with the compass needle when no current flows through the wire. In other words, orient wire A and the compass exactly as shown in Figure 5-38.

7. Watch the compass needle very closely and close the slide switch. Does the needle deflect clockwise (cw) or counterclockwise (ccw)? ____________.

8. Apply the left-hand rule for conductors to wire A. According to this rule, the magnetic field in front of the wire points _________ (up/down) at the point where the compass is setting. Does the needle of the compass deflect slightly in the direction of the magnetic field? That is, does it attempt to line up with the field around the conductor? ____________.

9. Open the slide switch. Disconnect wire B from the POS terminal and connect it to the NEG terminal. Will this change the direction of current flow through wire A? ____________.

10. Watch the compass needle closely and close the slide switch. Does the needle deflect clockwise or counterclockwise? ________________.

11. Apply the left-hand rule for conductors to wire A. Has the direction of the magnetic field changed? ____________.

Discussion

The 100-ohm resistor allows 100 mA of current to flow from the +10 volt supply. This is a relatively low current. It produces a very weak magnetic field around wire A. In Step 7 the compass needle attempts to align with this field by deflecting in a counterclockwise direction. When you applied the left-hand rule for conductors, you found that the field points down in front of the wire and up in back of the wire. The compass needle attempts to line up with this field. However, the field is not quite strong enough to overcome the Earth's magnetic field. Consequently, the needle does not deflect a full 90° as it would if it were not for the Earth's magnetic field.

In Steps 9, 10, and 11, the direction of current flow is reversed. This reverses the magnetic field and causes the needle to deflect clockwise. Again the field is too weak to produce a full 90° deflection. In the next part of this experiment, you will learn how to make the field stronger.

Procedure (Continued)

12. Cut a piece of cardboard (not supplied) to the shape and size shown in Figure 5-39A.

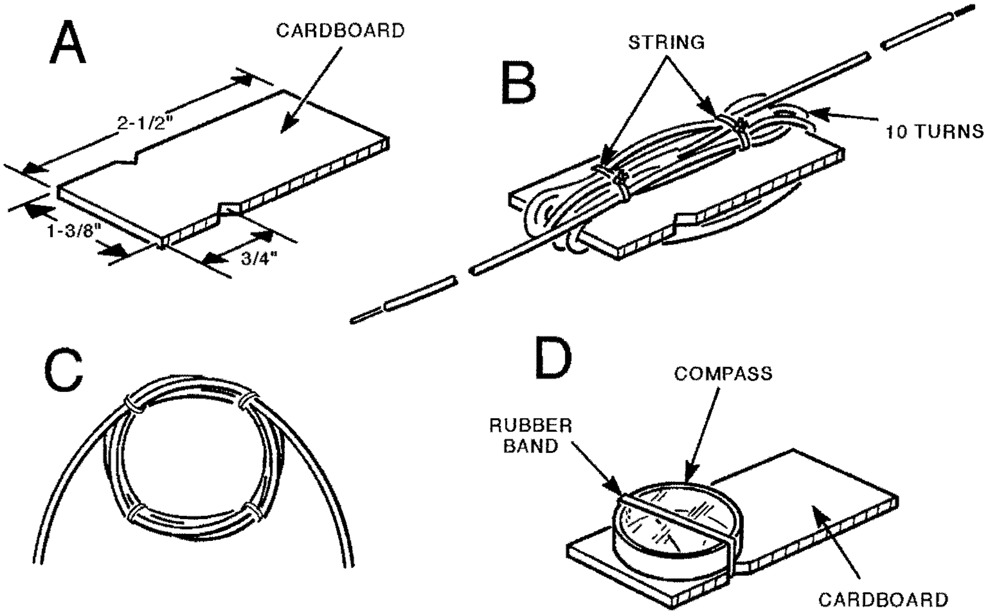

Figure 5-39
Preparing the coil and compass.

13. Use the remaining length of hook-up wire to form a coil by wrapping 10 turns of wire around the cardboard as shown in Figure 5-39B.

14. Tying the loops together with string, tape or wire to secure the coil. Remove the coil from the cardboard and shape it into a ring as shown in Figure 5-39C.

15. Secure the compass to the same cardboard with a rubber band or tape as shown in Figure 5-39D.

16. Use the + voltage control to set the voltage between the POS and GND terminals to +10 volts.

17. Construct the circuit shown in Figure 5-40.

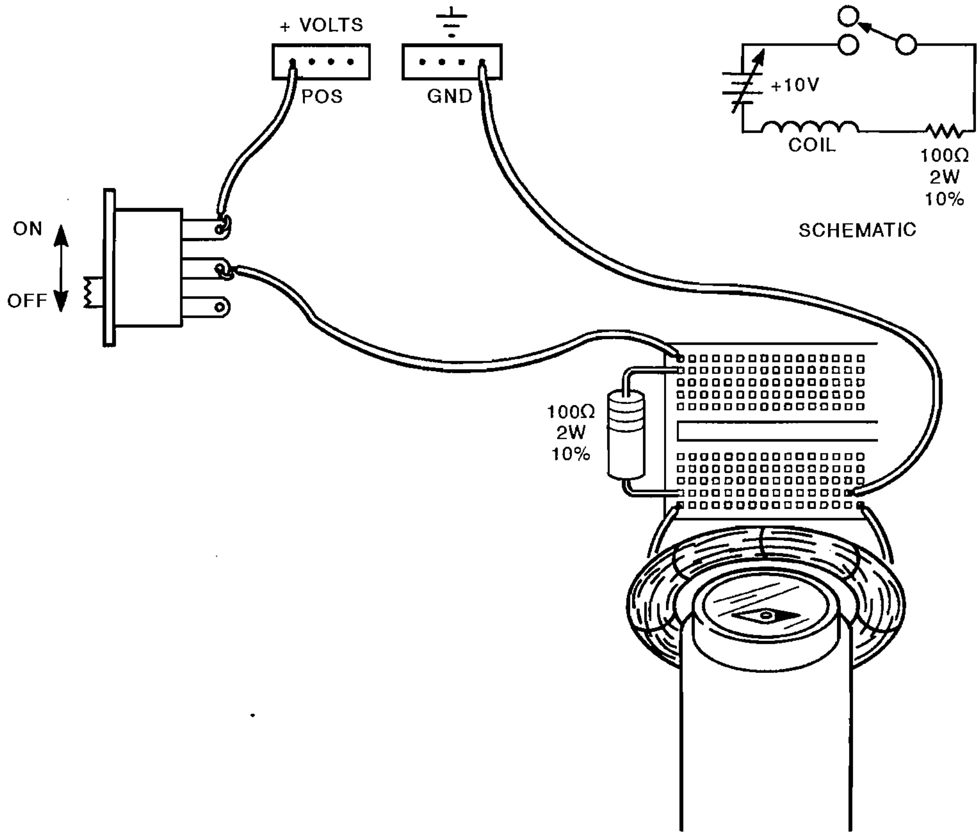

Figure 5-40
Experimenting with the electromagnetic coil.

18. Set the slide switch to the OFF (open) position so no current flows through the coil.

19. While no current is flowing, orient the coil and compass so the compass needle points toward the turns of wire as shown in Figure 5-40.

20. Close the slide switch so current now flows through the coil. What happens to the compass needle when you closed the switch? ____________________
____.

Is the deflection greater than it was when you used a single strand of wire? __________ Why? ____
____.

21. Determine which direction current flows in the circuit. Current flows __________ the left end of the coil.
(into/out of)

22. Determine which direction current flows through your coil. Wrap the fingers of your left hand in this direction. Hold your thumb at a right angle to your fingers. Your thumb now points toward the ____________ pole of your coil. To verify this, use the compass to check this pole.

23. Make sure the slide switch is off. Then replace the 100 ohm resistor with the 470 ohm resistor. This increases the resistance of the circuit. With 10 volts applied, the current in this new circuit will be ____________ mA.

24. Carefully align the compass in the coil as before. Watch the compass needle while you turn the slide switch on. The compass needle deflects __________
(more/less)
than it did before. Why? ____
____
____.

25. Make sure the slide switch is off. Then replace the 470 ohm resistor with the 1000 ohm resistor. This increases the resistance of the circuit. With 10 volts applied, the current in this new circuit will be ____________ mA.

26. Carefully align the compass in the coil as before. Watching the compass needle while you turn the slide switch on. The compass needle deflects __________
(more/less)
than it did before. Why? ____
____
____.

27. Earlier you learned that magnetomotive force (mmf) can be measured in ampere-turns. Determine the mmf produced in the coil with each of the following series resistances:

Resistance	**mmf**
100 Ω	________ ampere-turns
470 Ω	________ ampere-turns
1000 Ω	________ ampere-turns

28. Switch the Trainer OFF.

Discussion

In Step 20, the needle deflected to a full 90° from the coil windings. Here, the deflection is much greater than it was in Step 7 because the magnetic field is much stronger. The current in Step 20 is still 100 mA because the voltage is 10 volts and the resistance is 100 ohms. Because the voltage is positive, current flows from ground, through the coil and up through the 100 ohm resistor. Once you know which direction current flows, you can use the left-hand rule to determine the direction of the north pole of the coil. In Step 22 your thumb pointed toward the north pole of the coil.

In Steps 23 through 26, you increased the resistance in the circuit. This *decreased* the current and weakened the magnetic field. In turn, this decreased the amount of deflection that was displayed by the compass needle.

In Step 27, you determined the mmf of the coil for three series resistances. The mmf is equal to the number of turns in your coil multiplied by the current through the coil in amperes. Recall that there are 10 turns in the coil. You can use Ohm's Law to determine the current. You should notice that the amount of mmf is *directly* proportional to the amount of current.

Resistance	$I = \frac{E}{R}$	**Turns**	**mmf in Ampere-Turns**
100 Ω	$I = \frac{10}{100} = 0.1$ A	10	1
470 Ω	$I = \frac{10}{470} = 0.022$ A	10	0.22
1000 Ω	$I = \frac{10}{1000} = 0.01$ A	10	0.1

EXPERIMENT 14

Magnetic and Electromagnetic Devices

OBJECTIVES: *To demonstrate the characteristics of the permanent magnet, compass, reed switch, and relay.*

To verify that like magnetic poles repel and that unlike poles attract.

To demonstrate a practical circuit with the relay and reed switch.

To verify that a moving magnetic field induces an emf into a coil.

Introduction

Since you have been introduced to the fundamental rules that relate electricity and magnetism, its now time to have some fun! In this experiment you will work with some of the more practical electromagnetic devices used today. These include a magnetically activated (reed) switch, and a device in which a magnetic field is used to switch electrical contacts and perform a switching function in a circuit (the relay). You will apply these in some interesting applications, including an alarm circuit, electromechanical buzzer, and a circuit to demonstrate how electricity can be generated by electromagnetic induction. Because this is a relatively long experiment, you may want to perform it in two sessions. A good division is between steps 14 and 15.

Material Required

1 — Heathkit Analog Trainer
1 — Multimeter with test leads (analog preferred)
1 — Compass (#406-4)
1 — Permanent magnet (#474-1)
1 — Magnetic Reed Switch (#65-24)
1 — Relay (#69-136)
1 — #49 light bulb (#412-16)
1 — Lamp socket (#434-21)
1 — 100 Ω, 5%, 2-watt resistor (brown-black-brown-gold)
1 — Slide switch with soldered wires (#60-2)
Soldering iron and solder
#22 copper wire

Procedure

1. Use a string or thread to suspend the permanent magnet as shown in Figure 5-41. After a few moments, it will come to rest with one flat surface pointing north and the other pointing south. Mark the north pole (side facing north) with a small piece of tape.

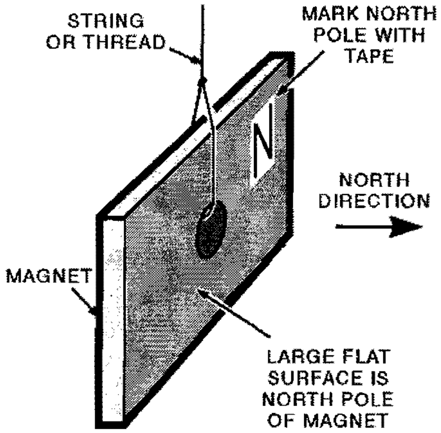
STRING OR THREAD
MARK NORTH POLE WITH TAPE
N
NORTH DIRECTION
MAGNET
LARGE FLAT SURFACE IS NORTH POLE OF MAGNET

Figure 5-41

A permanent magnet suspended by a string acts like a compass and aligns itself in a north-south direction.

2. Bring the north pole of the permanent magnet near the north pole end of the compass needle. The north pole of the compass is ______________ by the north pole of the permanent magnet. attracted/repelled

3. Pull the magnet away and allow the compass to realign in a north-south direction. Bring the north pole of the magnet near the south pole end of the compass needle. The south pole of the compass is ______________ by the north pole of the magnet. attracted/repelled

4. Locate the magnetic reed switch and examine its construction. Use an ohmmeter to measure the resistance between the two leads of the reed switch while the switch is not exposed to a magnetic field. The resistance is ____________ .

5. Leave the ohmmeter leads attached to the reed switch. Hold the permanent magnet several inches from the reed switch. Turn the magnet so that it is at a right angle to the reed switch as shown in Figure 5-42. Slowly move the magnet closer to the reed switch while you observe the ohmmeter reading. When the magnet is about 1/4 to 1/2 inch from the reed, the switch closes and the ohmmeter reading drops to ___________ ohms. Pull the magnet away and the ohmmeter reading returns to ____________ ohms.

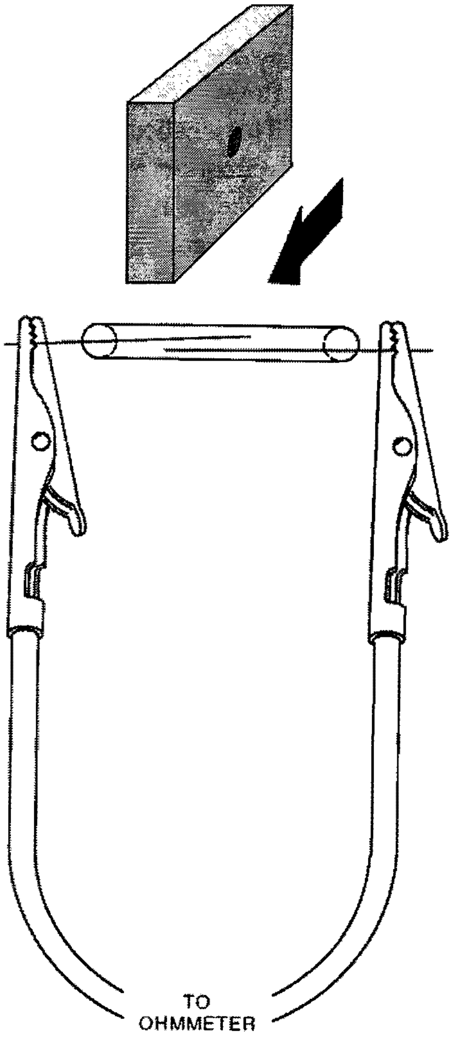

Figure 5-42
Closing the read switch.

Discussion

By experimenting with the magnet and compass you demonstrated that like poles repel and unlike poles attract. In Steps 4 and 5, you examined the operation of the reed switch. You verified that like any other switch it has infinite resistance when it is open and zero resistance when it is closed. In Step 5 you found that the reed switch can be closed by a magnetic field.

You will now continue this experiment by examining another important magnetic device—the relay. As you learned earlier, the relay consists of a coil with one or more sets of switch contacts. When current flows through the coil, it develops a magnetic field which closes the switch contacts. This is called the energized state. If the current falls below a certain level, the relay de-energizes and the switch contacts open. The amount of current necessary to cause the relay to energize is called the *pull-in current.* Once it is energized, it requires less current to hold the relay energized than it does to initially cause the relay to energize. Thus, you can decrease the current somewhat below the pull-in value, without de-energizing the relay. Of course, if you decrease the current is decreased too far, the relay will de-energize. The current at which this happens is called the *drop-out current.* The next part of this experiment examines the characteristics of the relay that is provided with this course.

Procedure (Continued)

6. Set the reed switch and magnet aside and locate the relay (69-136).

7. Observe the construction of the relay. If you cannot physically see inside your relay, refer to Figure 5-43A. Compare the construction of the relay with the schematic diagram shown in Figure 5-43C. Notice that pins 4 and 5 connect to the coil potion of the relay while pins 1, 2, and 3 connect to the switch. Which pin goes to the movable arm of the switch? _________. To which pin is pin 3 connected when the relay is de-energized? _________. To which pin is pin 3 connected when the relay is energized? _________.

8. Cut five 3-inch lengths from the white hook-up wire. Strip 1/4-inch of insulation from each end of each wire. Solder one end of each wire to each of the five pins on the relay.

9. Connect the ohmmeter between pins 4 and 5 of the relay. What is the resistance of the coil? ___________ ohms.

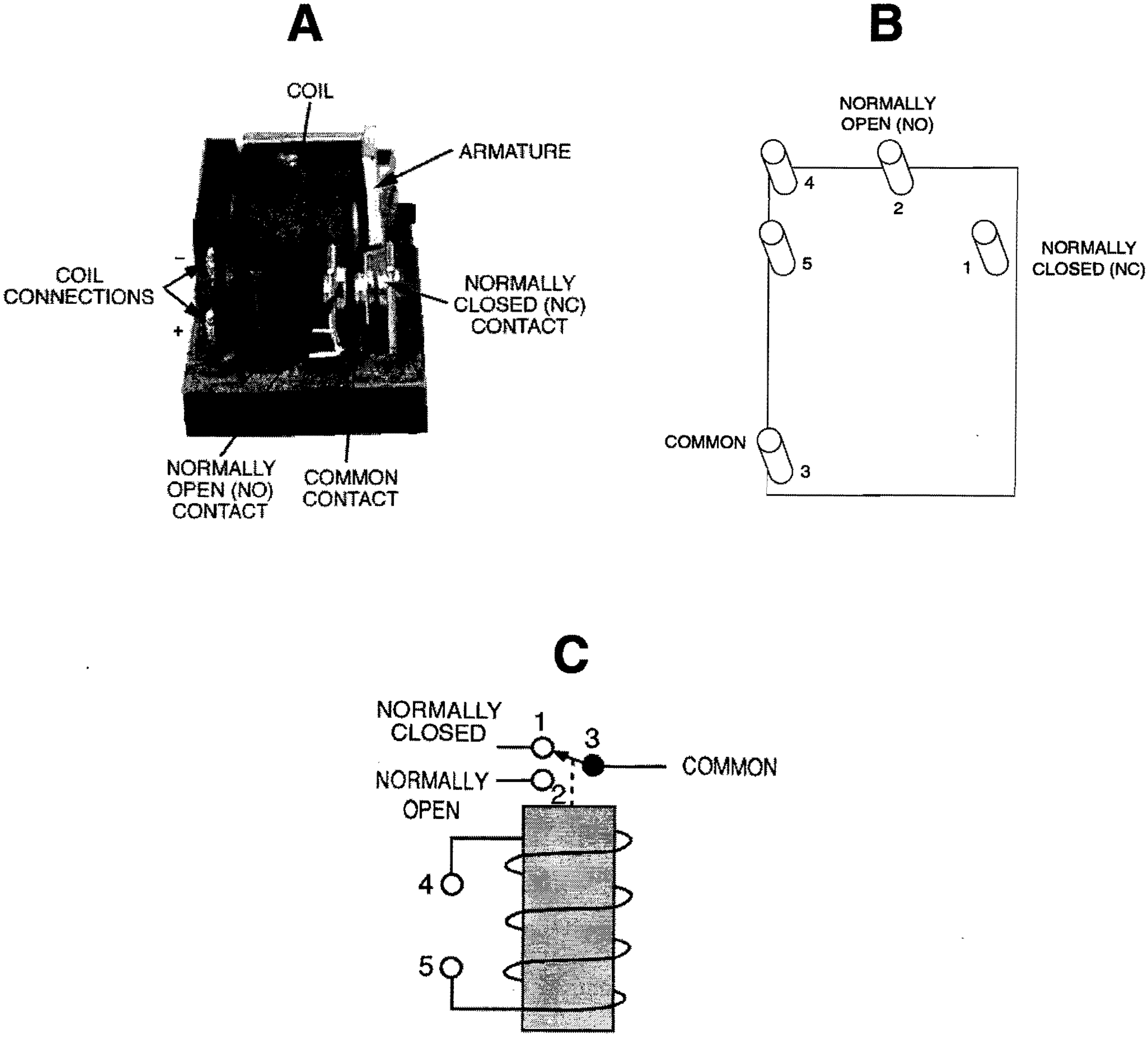
A
COIL
ARMATURE
COIL CONNECTIONS
–
+
NORMALLY CLOSED (NC) CONTACT
NORMALLY OPEN (NO) CONTACT
COMMON CONTACT
B
NORMALLY OPEN (NO)
4
2
5
1
NORMALLY CLOSED (NC)
COMMON
3
C
NORMALLY CLOSED
1
3
COMMON
NORMALLY OPEN
2
4
5

Figure 5-43
The relay.

10. Adjust the + voltage control on the Trainer to minimum voltage (fully ccw). Connect the circuit shown in Figure 5-44. Do not allow the clips to touch each other or other relay lugs.

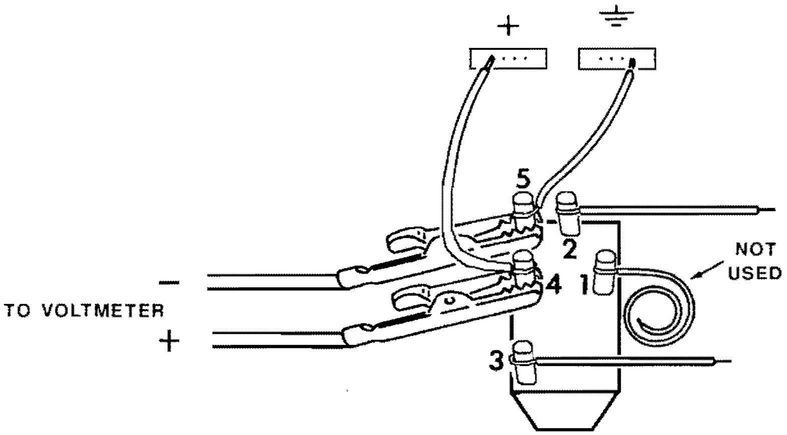

Figure 5-44
Determining the pull-in and drop-out currents.

11. Connect your ohmmeter between pins 2 and 3 of the relay.

12. Switch the Trainer on and very slowly increase the + voltage while you watch both the ohmmeter reading. Increase the voltage to the point where the relay just energizes as indicated by a low ohmmeter reading (you may be able to hear the relay contacts open/ close with a clicking sound). Connect your voltmeter between pins 4 and 5 of the relay. The voltage across the coil when the arm first pulls in (down) is ____________ volts.

13. Use the voltage you measured in Step 12 and the resistance you measured in Step 9 to compute the current which flows through the coil at the instant the relay energized. The current is ____________ mA. This is called the ____________ current.

14. Connect your ohmmeter between pins 2 and 3 of the relay.

15. Slowly decrease (ccw) the + voltage until the coil just de-energizes as indicated by a high ohmmeter reading.. The voltage across the coil when the arm first releases is ____________ volts.

16. Use the voltage you measured in Step 15 and the resistance you measured in Step 9 to compute the current which flowed through the coil at the instant the relay de-energized. This current is ____________ mA. This is called the ____current.

Discussion

The resistance of the relay is 950 ohms ±10%. In Step 12, the relay should have pulled in when the voltage across it was about 6 volts. This corresponds to a pull-in current of:

$$I = \frac{E}{R} = \frac{6\ \text{V}}{950\ \Omega} = 6.3\ \text{mA}$$

In Step 15, you measured the voltage at which the relay releases. A value of about 3.5 volts is common. This corresponds to a drop out current of about:

$$I = \frac{E}{R} = \frac{3.5\ \text{V}}{950\ \Omega} = 3.7\ \text{mA}$$

Relays are used in a wide variety of applications. A practical application which also uses a reed switch is shown in Figure 5-45. This is a simple burglar alarm circuit similar to ones used in some homes. The purpose of the circuit is to light the alarm lamp L_1, whenever the protected door or window is opened. The sensor which detects the condition of the door is a reed switch. The magnet is located on the door while the reed switch is placed in the door frame. When the door is closed, the magnet forces the reed switch to close. But when the door is opened, the magnet moves away and the reed switch opens.

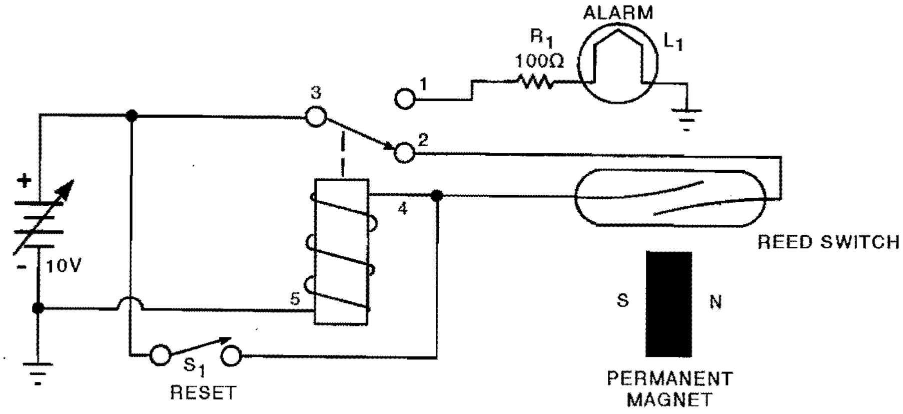

Figure 5-45
Schematic for a burglar alarm circuit.

To activate the circuit, you close reset switch S_1. This provides a path for current flow through the relay and allow it to energize. When the relay energizes, the movable arm connected to pin 3 is pulled down to make contact with pin 2. At this time the light is off. If the door is closed, the reed switch is closed. This provides a path for current flow from ground, through the relay coil, the reed switch, and contacts 2 and 3 of the relay to the positive side of the power supply. Since the closed contacts of the reed switch now conduct current to keep the relay energized, you can now open S_1 because the current path through S_1 is no longer needed. The circuit is now activated. If the door (reed switch) is opened for any reason, the alarm light will turn on.

With the circuit activated, the closed reed switch holds the relay energized. If you move the magnet away from the reed switch which causes it to open, this breaks the path for current through the relay. The relay de-energizes and the movable arm connected to pin 3 falls back to pin 1. This applies 10 volts to the alarm lamp which forces it to light. Notice that re-closing the reed switch (door) will not turn off the alarm. Even if the reed contacts close, the relay remains de-energized until you also close S_1. That is, the circuit can be reset only by closing the reed switch (door) *while* the reset switch is *also* closed. After the reed switch (door) and S_1 (reset switch) have been closed simultaneously, S_1 can be opened, and the circuit is again "armed" and ready.

Procedure (Continued)

17. Make sure the Trainer power is OFF. Then connect the circuit shown in Figure 5-46. Set the reset slide switch to the off position.

18. Turn the trainer on. Adjust the voltage between the POS and GND terminals to 10 volts. At this point, is the alarm light on or off? ____________ .Is the relay energized or de-energized? ____________ .

19. Move the magnet away from the reed switch. Set the reset slide switch to the on position. Does the relay energize? ____________ .

20. Set the reset slide switch back to the off position. Does the relay de-energize? ____________ . Is the circuit now activated and ready for use? ____________ .

21. Set the magnet against the center of the reed switch. Make sure that it is at a right angle to the reed switch, as shown in Figure 5-46. When you have the magnet properly positioned, the reed switch should be closed. Does the relay energize? ____________ .

22. Leave the magnet in place against the (closed) reed switch. Set the reset slide switch back to the on position. Does the relay energize? ____________ .

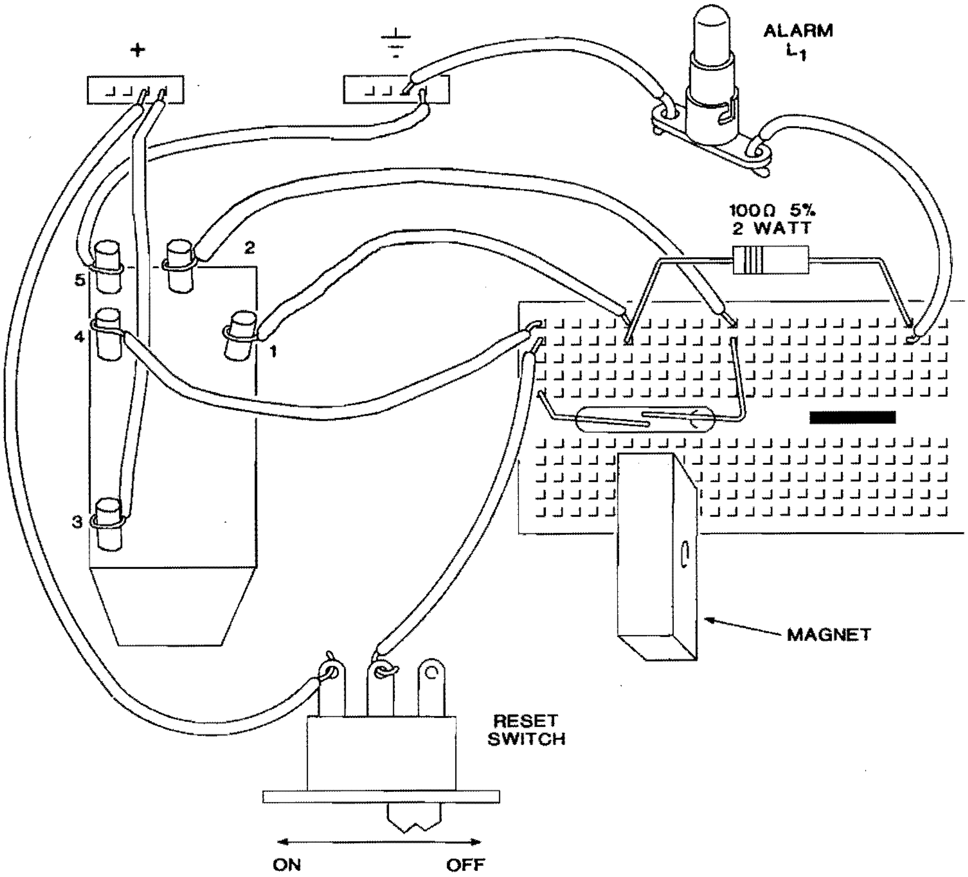

Figure 5-46
Wiring diagram for the burglar alarm circuit.

23. Set the reset slide switch back to the off position. Does the relay remain energized? ____________ . Is the circuit now activated and ready for use? ____________ .

24. Slowly move the magnet away from the reed switch to simulate a door opening. Does the alarm light come on? ____________ . Can the alarm light be turned off by setting the magnet back into place? ____________ . How can the circuit be reset? ____ ____ .

Discussion

Refer to the schematic diagram in Figure 5-45 as you read the following discussion. In Step 18, the alarm light should be on because the relay is de-energized. When you set the slide switch to the on position in Step 19, it caused the relay to energize and the lamp turned off. However, because the magnet is not in place, the relay de-energizes again in Step 20 when you turned the slide switch off. In Step 21, you used the magnet to close the reed switch. However, this, in itself, is not enough to energize the relay. The relay does energize in Step 22 when you closed the slide switch. Also, because a current path now exists through the reed switch and the relay contacts, the relay remains energized in Step 23 when you opened the slide switch. At this point, the circuit is activated and ready for use. In Step 24, you simulated a door opening by moving the magnet. This allowed the reed switch to open and remove current from the relay. The relay de-energized which lighted the alarm light. Replacing the magnet does not reset the circuit (turn off the light). However, you can reactivate the circuit by repositioning the magnet against the reed switch and momentarily closing the slide switch.

The relay can illustrate two additional principles. However, be aware that this relay would not normally be used in either of these applications. Nevertheless, the next part of this experiment use the relay to demonstrate the principle of the **electric buzzer** and the **generator**.

Procedure (Continued)

25. Turn the + voltage control fully counterclockwise. Connect the circuit shown in Figure 5-47. Gradually turn the + voltage control clockwise. What happens when you reach the pull-in current? ______________________________

    ____.

    Why? ____.

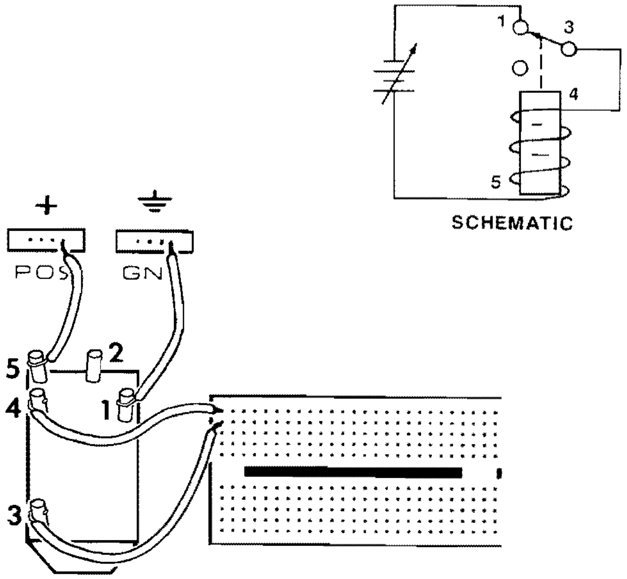

Figure 5-47
The electric buzzer.

26. Switch the Trainer power OFF and disconnect the relay from the Experimenter. Connect the voltmeter* between pins 4 and 5 of the relay. Set the voltmeter to its lowest dc voltage range (2.5 volt range or lower).

27. Observe the voltmeter movement while you move the permanent magnet up and down over the top of the relay as shown in Figure 5-48. Does the needle deflect? ____________ How do you account for this? ____________________ ____________________________________.

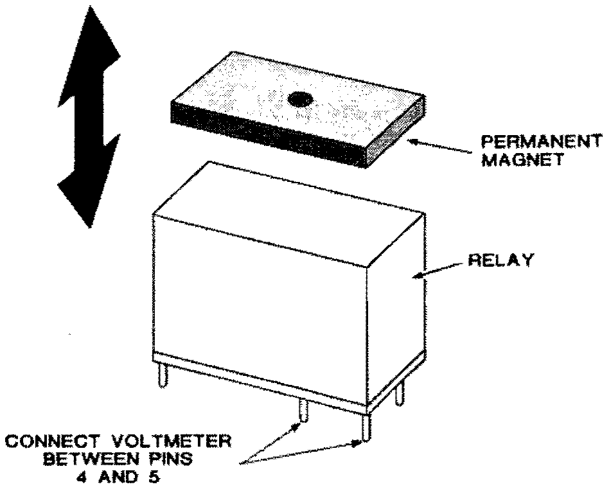

Figure 5-48
Demonstrating electromagnetic induction.

28. Turn the magnet so its north pole is toward the top of the relay. As you move the magnet down toward the relay, the meter deflects ______________. As
up scale/down scale
you move the magnet up away from the relay, the meter deflects ______________. From this you can conclude that when the direction of the
up scale/down scale
relative motion between the relay and magnet reverses, the induced voltage ____________________ polarity.
reverses/maintains the same

29. Turn the magnet over so that its south pole is toward the top of the relay. As you move the magnet down toward the relay, the meter deflects ______________. Is this the same direction that the meter deflected when you
up scale/down scale
moved the north pole down toward the relay in Step 28? ____________.

---

* For this procedure, an analog voltmeter (with a needle movement) is necessary.

30. Move the magnet very slowly up and down and note the amount of deflection. Now move the magnet rapidly up and down and note the amount of deflection. Which produces the greatest emf? ______________________________
____ .

31. Hold the magnet stationary and move the relay up and down under the magnet. Does the meter still deflect? ____________ .

Discussion

In Step 25, you connected the relay as a buzzer. Refer to the schematic shown in Figure 5-47. When the current reached the pull-in value, the relay energized and pin 3 was pulled down away from pin 1. This broke the path for current flow and the relay de-energized. This, in turn, reconnected the relay to the power supply and the relay energized again. Thus, the relay alternately energized and de-energized many times each second. The buzz that you heard was caused by the armature as it vibrated back and forth. You could feel this vibration if you placed your finger against the armature. While relays are not normally designed to be used as a buzzer, many are designed for exactly that purpose. The buzzer in your car which sounds when you leave your keys in the ignition, or leave the lights on, uses this same principle.

In Steps 26 through 31, you demonstrated the principle of electromagnetic induction. You moved a magnet so that its field cut the turns of the coil on the relay. This induced an emf into the coil which you could observe on the meter. In Step 28 you saw that when you reversed the direction of the motion, the polarity of the induced emf also reversed. In Step 29 you saw that you could also reverse the polarity of the magnetic field to reverse the polarity of the induced emf. You proved in Step 30 that the magnitude of the induced emf is proportional to the speed with which you move the magnet. Finally, in Step 31, you demonstrated that the induced emf exists whether you move the magnet or the relay. That is, all that is necessary is relative motion between the magnetic field and the coil.

SUMMARY

Action-at-a-distance is explained in terms of a field. Because a magnet can affect objects at a distance, it appears to be surrounded by a magnetic field. This field is assumed to be made-up of lines of force called flux lines.

Magnets have north and south poles. The flux lines leave the magnet at the north pole and enter the magnet at the south pole and form complete loops. The flux lines cannot cross each other and tend to form the smallest possible loops.

Like magnetic poles repel; unlike poles attract.

All materials are classified as either ferromagnetic, paramagnetic, or diamagnetic. Ferromagnetic materials are strongly attracted by magnetic fields; paramagnetic materials are only slightly attracted; and diamagnetic materials are slightly repelled. Generally, paramagnetic and diamagnetic materials are non-magnetic.

When an electrostatic charge moves, a magnetic field is developed. The electron spins on its axis and produces a magnetic field. In most atoms, electrons with opposite spins pair off so that their magnetic fields cancel. However, in iron, nickel, and cobalt, the two valence electrons spin in the same direction and their fields add.

These magnetic atoms bunch in tiny groups called domains. Normally, these domains are arranged haphazardly and their fields cancel. However, when they are subjected to a magnetic field, the domains align in the same direction to create a magnet.

Magnetism and electricity are closely related. Current flow produces a magnetic field and a moving magnetic field can produce current flow.

You can use the left-hand rule for conductors to determine the direction of the magnetic field that is caused by current flow. This rule states: Grasp the conductor in your left hand with your thumb pointing in the direction of current flow. Your fingers now point in the direction of the flux lines.

You can strengthen and concentrate the magnetic field around the conductor by winding the conductor as a coil. The result is called an electromagnet which has many of the characteristics of a permanent magnet.

The left-hand rule for coils helps you determine the north pole of the electromagnet. It states: Grasp the coil in your left hand with your fingers wrapped around it in the direction that current is flowing. Your thumb now points toward the north pole of the coil.

Several magnetic quantities are important. *Permeability* is the ease with which a substance accepts lines of force. Its reciprocal is called *reluctance*. *Flux* is the total lines of force around a magnet. *Flux density* refers to the amount of flux per unit of area. *Magnetomotive force* is the force which produces the flux in a coil. *Field intensity* is the amount of mmf per unit of length of the coil.

When one body has an electrostatic or magnetic field, it can induce a change in another body without actually touching the other body. This is called induction.

A magnet can induce a magnetic field into a ferromagnetic body without touching it. This is called magnetic induction. When the magnet is taken away, a magnetic field remains in the ferromagnetic body. This is called *residual magnetism*. The ability of a substance to retain a magnetic field after you remove the magnetizing force is called *retentivity*.

When a conductor moves across a magnetic field, an emf is induced into the conductor. This is called *electromagnetic induction*.

The magnitude of the induced emf is proportional to the rate at which the conductor cuts the magnetic lines of force. The more lines per second that are cut, the higher the induced emf.

The left-hand rule for generators helps you determine the polarity of the induced emf. To use this rule, point your thumb in the direction that the conductor is moving. Then point your index finger in the direction of the flux lines. If you now place your middle finger at right angles to your thumb and index finger, it points in the direction in which current flows through the conductor.

A device which uses electromagnetic induction to convert mechanical energy to electrical energy is called a generator. A generator may produce AC or DC, depending upon how it is constructed. An AC generator is called an alternator. The DC generator uses commutators and brushes to convert AC to DC.

There are many other devices which use magnetic or electromagnetic principles.

A *relay* uses an electromagnet to close switch contacts.

The *record pickup* uses a magnet and moving coil to convert stylus vibrations into voltage variations which can be amplified. The *loudspeaker* uses a similar arrangement to convert these amplified voltage variations back to sound.

A tape recorder uses an electromagnet as a *record* head. Current variations are applied to an electromagnet which creates corresponding magnetic patterns on a length of tape. In the playback mode, the head converts to a tiny generator. The magnetic variations on the tape induce tiny voltage variations into the coil. These voltage variations are amplified and applied to the loudspeaker where they are converted back to sound.

A *motor* converts electrical energy to mechanical energy. Current passes through a coil to produce an electromagnetic field. This field interacts with a permanent magnet's field. As a result, the coil is forced to move. Proper design achieves a constant circular motion.

A meter works on the same principle as the motor. Here, springs restrict the movement of the coil. A pointer that is attached to the coil moves in front of a scale to indicate the current through the meter.

Motor action is also used to deflect the electron beam in TV receivers, TV cameras, and radar indicators.

The right-hand motor rule helps you determine the direction of movement of the coil in the motor or meter, or the direction of deflection of the electron beam. To use this rule, you hold your thumb, index finger, and middle finger of your right hand at right angles to each other. If you point your index finger in the direction of the magnetic field and the middle finger in the direction of electron flow, your thumb will point in the direction in which the conductor (or electron beam) moves.

UNIT EXAMINATION

1. Iron readily accepts magnetic flux. Therefore, iron is:

   A. ferromagnetic and has a high permeability.
   B. paramagnetic and has a high reluctance.
   C. ferromagnetic and has a low permeability.
   D. paramagnetic and has a low reluctance.

2. Which magnetic quantity is expressed in ampere-turns?

   A. Flux density.
   B. Field intensity.
   C. Magnetizing force.
   D. Magnetomotive force.

3. When you use the left-hand rule for conductors, your thumb points:

   A. toward the north pole of the conductor.
   B. in the direction of the magnetic field.
   C. in the direction of current flow.
   D. in the direction which the conductor will move.

4. Which of the following will increase the strength of the magnetic field in the core of a coil?

   A. Increasing the current through the coil.
   B. Increasing the number of turns in the coil.
   C. Placing a piece of ferromagnetic material in the core.
   D. All the above.

5. A device which uses electromagnetic induction to convert mechanical energy to electrical energy is called:

   A. an alternator.
   B. a motor.
   C. a magnet.
   D. an electromagnet.

6. Refer to the circuit shown in Figure 5-27. When switch S_1 is closed:

   A. the relay contacts open.
   B. the top of the relay core becomes a magnetic north pole.
   C. the bottom of the relay core becomes a magnetic north pole.
   D. the generator is disconnected from the load.

7. Refer to the circuit shown in Figure 5-45. Lamp L_1 lights anytime that:

   A. switch S_1 is closed.
   B. switch S_1 is opened.
   C. the reed switch is closed.
   D. both the reed switch and S_1 are open.

8. When a conductor moves through a magnetic field, an emf is induced in the conductor. Which of the following statements regarding the induced emf is not true?

   A. The greatest emf is produced when the conductor moves perpendicular to the magnetic field.
   B. The slower the conductor moves, the greater the emf.
   C. The stronger the magnetic field, the greater the emf.
   D. The longer the conductor, the greater the emf.

9. Figure 5-49 shows a conductor in motion at five different positions in a magnetic field. Maximum voltage is induced in the conductor as it moves through:

   A. point 1.
   B. point 2.
   C. point 3.
   D. point 5.

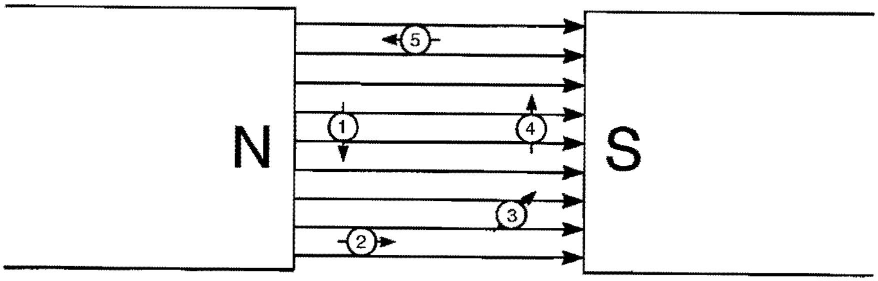

Figure 5-49
Diagram for Questions 9 and 10.

10. Refer again to Figure 5-49. The same polarity emf is induced at points:

    A. 1 and 4.
    B. 3 and 4.
    C. 3 and 5.
    D. 1 and 5.

11. When you use the left-hand rule for generators, your thumb points in the direction of the:

    A. conductor motion.
    B. induced current.
    C. magnetic field.
    D. north magnetic pole.

12. When you use the right-hand rule for motors, your thumb points in the direction of the:

    A. conductor motion.
    B. magnetic field.
    C. current flow.
    D. north magnetic pole.

13. Besides the motor, which of the following devices uses motor action to perform a useful function?

    A. The relay.
    B. The meter movement.
    C. The pickup cartridge of a record player.
    D. The playback head of a tape recorder.

14. Besides the generator, which of the following uses generator action to perform a useful function?

    A. The DC motor.
    B. The meter movement.
    C. The moving-coil pickup cartridge in a record player.
    D. The relay.

15. Which of the following rules can be used to determine the direction that a moving electron will deflect when it enters a magnetic field?

    A. Left-hand rule for conductor.
    B. Left-hand rule for coils.
    C. Left-hand rule for generators.
    D. Right-hand rule for motors.

16. Magnetic materials, such as magnetite and lodestone are examples of:

    A. artificial magnets.
    B. natural magnets.
    C. temporary magnets.
    D. alnico magnets.

17. Which of the following is not a characteristic of lines of flux?

    A. Lines of flux always form complete loops.
    B. Lines of flux are random and have no polarity.
    C. Lines of flux cannot cross each other.
    D. Lines of flux tend to form the smallest possible loops.

18. The term used to indicate the relationship between mmf, measured in ampere turns, and the length of a coil is:

    A. flux density.
    B. reluctance.
    C. retentivity.
    D. field intensity.

19. Faraday's Law states that the voltage induced in a conductor:

    A. is inversely proportional to the rate at which a conductor cuts the magnetic lines of force.
    B. depends entirely upon the material from which the conductor is made.
    C. is directly proportional to the rate at which a conductor cuts the magnetic lines of force.
    D. is greatest when the conductor moves parallel to the magnetic lines of force.

20. The four basic parts of a simple dc generator are the:

    A. commutator, brushes, loop or coil, and armature.
    B. brushes, loop or coil, permanent magnet, and connectors.
    C. commutator, brushes, loop or coil, and permanent magnet.
    D. commutator, loop or coil, permanent magnet, and power source.

21. As the strength of a magnetic field increases, the amount of emf induced in a conductor passing through the field:

    A. increases.
    B. decreases.
    C. remains the same.

22. If the speed of a conductor increases as it passes through a magnetic field, the emf induced in the inductor:

    A. increases.
    B. decreases.
    C. remains the same.

23. If the length of a conductor passing through a magnetic field increases, the emf induced in the conductor:

    A. increases.
    B. decreases.
    C. remains the same.

EXAMINATION ANSWERS

1. A — Iron is ferromagnetic and has a high permeability.

2. D — Magnetomotive force is expressed in ampere-turns.

3. C — When you use the left-hand rule for conductors, your thumb points in the direction of current flow. This is illustrated in Figure 5-12.

4. D — All of the methods mentioned in answers A, B, and C increase the strength of the magnetic field around the coil.

5. A — An alternator is an AC generator. It converts mechanical energy to electrical energy.

6. B — When you apply the left-hand rule for coils to the relay, you find that the top of the core is a north magnetic pole when switch S_1 is closed.

7. D — The lamp lights when the relay is de-energized. There are two current paths for the relay: one through S_1; the other through the reed switch and the relay contacts. Thus, the relay must be de-energized when both the reed switch and S_1 are open.

8. B — The emf is proportional to the speed that the conductor moves. Thus, the *faster* the conductor moves, the *greater* the emf.

9. A — At point 1, the conductor is moving perpendicular to the lines of force. Thus, it is cutting the maximum number of lines per second at this time. Consequently, the induced emf is maximum at this point.

10. B — At both points 3 and 4 the conductor is moving up past the south pole. Consequently, the same polarity of emf is induced at these two points. Of course, the magnitude of the emf is greater at point 4.

11. A — When you use the left-hand rule for generators, your thumb points in the direction that the conductor is moving. This is illustrated in Figure 5-22.

12. A — When you use the right-hand rule for motors, your thumb points in the direction that the conductor will move. This is illustrated in Figure 5-33.

13. B — The meter movement uses the same action as the motor to move a needle in front of a scale.

14. C — In the moving-coil pickup, a tiny voltage is induced into the moving-coil as it vibrates in the field of a permanent magnet. While the voltage induced into the coil is much smaller than that produced by a generator, the principle is the same.

15. D — The right-hand rule for motors is used to determine the direction that a moving-electron will deflect when it enters a magnetic field.

16. B — Both magnetite and loadstone are examples of magnetic materials that are found in nature.

17. B — Magnetic lines of flux have a polarity. The polarity is indicated as either the north or the south pole, and the direction of the lines of flux is assumed to be from the north to the south.

18. D — Field intensity is the term that is used to indicate the number of ampere turns per inch in a coil.

19. C — Faraday's Law states that the voltage induced into a conductor is directly proportional to the rate at which the conductor cuts the magnetic lines of flux.

20. C — A simple DC generator consists of a commutator, loop or coil, brushes, and a permanent magnet. A basic DC generator is shown in Figure 5-25B.

21. A — According to Faraday's Law, the rate at which a conductor cuts lines of force determines the induced emf. If the number of lines of force is increased by increasing the strength of the magnetic field, the induced emf will also increase.

22. A — As the speed of the conductor increases, the rate at which the conductor cuts the lines of force also increases. This results in an increase in induced emf.

23. A — If a greater length of conductor passes through the lines of flux, the resulting induced emf will increase.

UNIT 6

ELECTRICAL MEASUREMENTS

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INTRODUCTION

This unit deals with electrical measurements. It explains the construction and operation of the most commonly used electrical measuring instrument—the volt-ohm-milliammeter (VOM), or multimeter. As the name implies, this instrument can measure voltage, resistance, and current. There are two basic types of VOM, or multimeter. One uses a mechanical, or analog meter movement as its display, while the other uses an electronic, or digital display. Other than the display, both meter types operate in a similar fashion. Because the analog meter is the more basic of the two types, this unit is mainly concerned with its operation. The heart of this instrument is a moving-coil meter movement like the one described in the previous unit on magnetism. In this unit you will take learn more about this type of meter movement and see how you can use it to measure current, voltage, and resistance.

UNIT OBJECTIVES

When you complete this unit, you will be able to:

1. List six parts of the moving-coil meter movement and explain the purpose of each.

2. Demonstrate how you should connect the ammeter, voltmeter, and ohmmeter to a circuit under test.

3. Given the full scale deflection and the meter resistance, calculate the proper value of shunt required to increase the current capability to a given value.

4. Given the full-scale deflection and the meter resistance, calculate the series dropping resistance that is required to increase the voltage capability to a given value.

5. Draw the schematic diagrams of a simple series ohmmeter and a simple shunt ohmmeter.

6. Define and calculate *meter sensitivity* for a given meter movement.

7. Explain how a single meter movement is used in a VOM to indicate current, voltage, and resistance.

8. Define voltmeter loading and explain how you can minimize its effects.

9. Name the components that increase the range of a voltmeter and an ammeter.

10. State at what point on a meter scale you can obtain the most accurate readings.

11. State the purpose of the "ZERO OHMS" variable resistor in an ohmmeter.

12. Name the three components that make up the most basic ohmmeter.

13. State how an ammeter can introduce an error when you use it to measure current.

14. Define the term parallax.

UNIT ACTIVITY GUIDE

	Completion Time
☐ Read "The Meter Movement."	
☐ Complete programmed review frames 1 through 10.	
☐ Read "The Ammeter."	
☐ Complete programmed review frames 11 through 25.	
☐ Read "The Voltmeter."	
☐ Complete programmed review frames 26 through 35.	
☐ Read "The Ohmmeter."	
☐ Complete programmed review frames 36 through 49.	
☐ Read "Multimeters."	
☐ Complete programmed review frames 50 through 60.	
☐ Perform Experiment 15.	
☐ Perform Experiment 16.	
☐ Study Summary.	
☐ Complete Unit Examination.	
☐ Check Examination Answers.	

THE METER MOVEMENT

The meter movement is the heart of the volt-ohm-milliammeter (VOM). The most popular type of meter movement is the permanent-magnet, moving-coil movement that was described in the previous unit. This device is also called the d'Arsonval movement after its inventor Arsene d'Arsonval. The first version, introduced in 1882, was called a galvanometer. It was delicate and somewhat crude. In 1888, Edward Weston introduced an improved version of the device which is similar to the designs used today.

Construction

Figure 6-1 shows the construction of the meter movement. Several important parts are listed. You will learn about each of these parts in detail, starting with the permanent magnet.

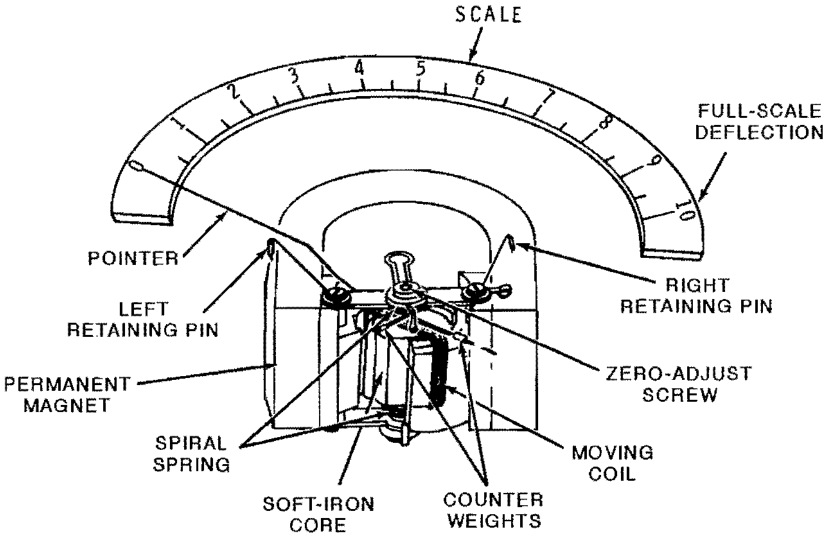
SCALE
0
1
2
3
4
5
6
7
8
9
10
FULL-SCALE DEFLECTION
POINTER
LEFT RETAINING PIN
RIGHT RETAINING PIN
PERMANENT MAGNET
ZERO-ADJUST SCREW
SPIRAL SPRING
MOVING COIL
SOFT-IRON CORE
COUNTER WEIGHTS

Figure 6-1
Permanent-magnet, moving-coil meter movement.

Figure 6-2 shows the permanent magnet system. A horseshoe magnet produces the stationary magnetic field. To concentrate the magnetic field in the area of the moving coil, pole pieces are added to the magnet. These are made of soft iron and have a very low reluctance. Consequently, the lines of flux tend to concentrate in this area as shown. Also, a stationary soft-iron core is placed between the pole pieces. Enough space is left between the pole pieces and the core so that the moving coil can rotate freely in this space. As you can see, the pole pieces and core restrict most of the flux to the area of the moving coil.

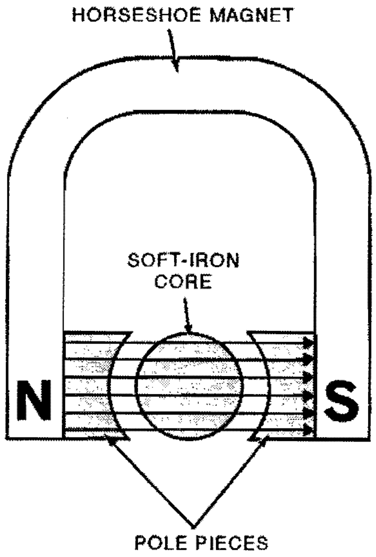
HORSESHOE MAGNET
SOFT-IRON CORE
N
S
POLE PIECES

Figure 6-2
The permanent magnet.

Figure 6-3 shows how the moving coil fits around the soft-iron core. The coil consists of many turns of extremely fine wire on an aluminum frame. The aluminum frame is very light so that little torque is needed to move it. The two ends of the coil connect to the leads of the ammeter, voltmeter, or ohmmeter.

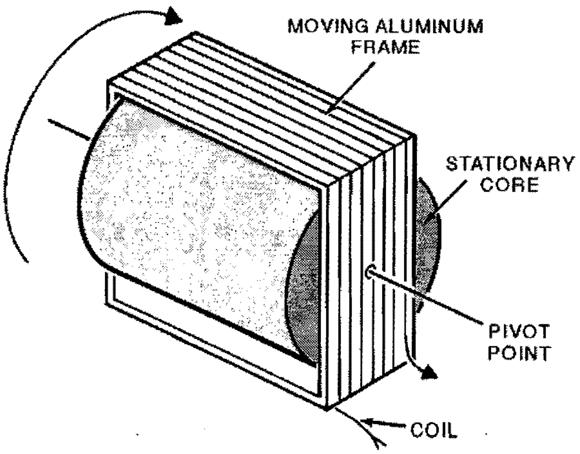
MOVING ALUMINUM FRAME
STATIONARY CORE
PIVOT POINT
COIL

Figure 6-3
The moving coil.

Figure 6-4 shows the details of the pointer assembly. The pointer is attached to the moving coil so that it moves when the coil does. Counterweights are often attached to the pointer so that a perfect balance is achieved. This makes the pointer easier to move and helps the meter read the same in all positions. A well balanced meter reads the same whether you hold it vertically or horizontally. Retaining pins on either side of the movement limit the distance that the pointer and other rotating parts can move. Two spiral springs at opposite ends of the moving-coil force the pointer back to the zero position when no current flows through the coil. In most movements, the spiral springs also apply current to the moving coil. The two ends of the coil connect to the inner ends of the spiral spring. The outer end of the rear spring is fixed in place. However, the outer end of the front spring connects to a zero-adjust screw. This allows you to set the pointer to exactly the zero point on the scale when no current flows through the coil.

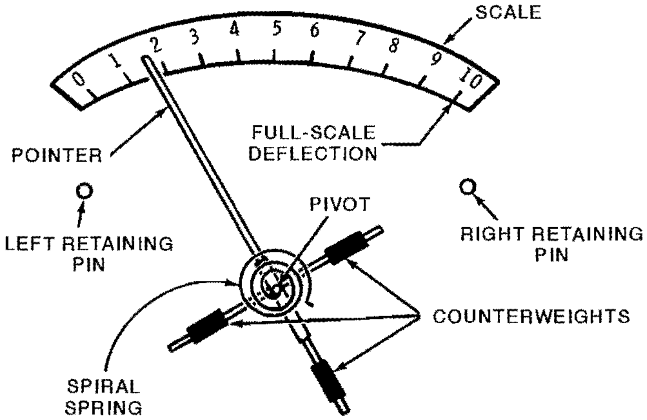

Figure 6-4
The pointer assembly.

The moving coil, pointer, and counterweight rotate around a pivot point. Jeweled bearings are used at this point, just as they are in a fine watch, to hold the friction to an absolute minimum.

Operation

Now that you have an idea of the meter's construction, you will next learn how it operates. In the previous unit, you learned that a conductor is deflected at a right angle to a stationary magnetic field if current flows through the conductor. This is the principle of the DC motor. You also learned a rule, called the right-hand motor rule, which describes this action. Figure 6-5 illustrates this rule and the motor action which causes the meter to deflect. An end view of one turn of the moving-coil is shown.

Current is forced to flow through the coil so that current flows "out of the page" on the left. Applying the right hand rule to the coil at this point, we find that the coil is forced up on the left and down on the right. This forces the pointer to move up scale or in the clockwise direction.

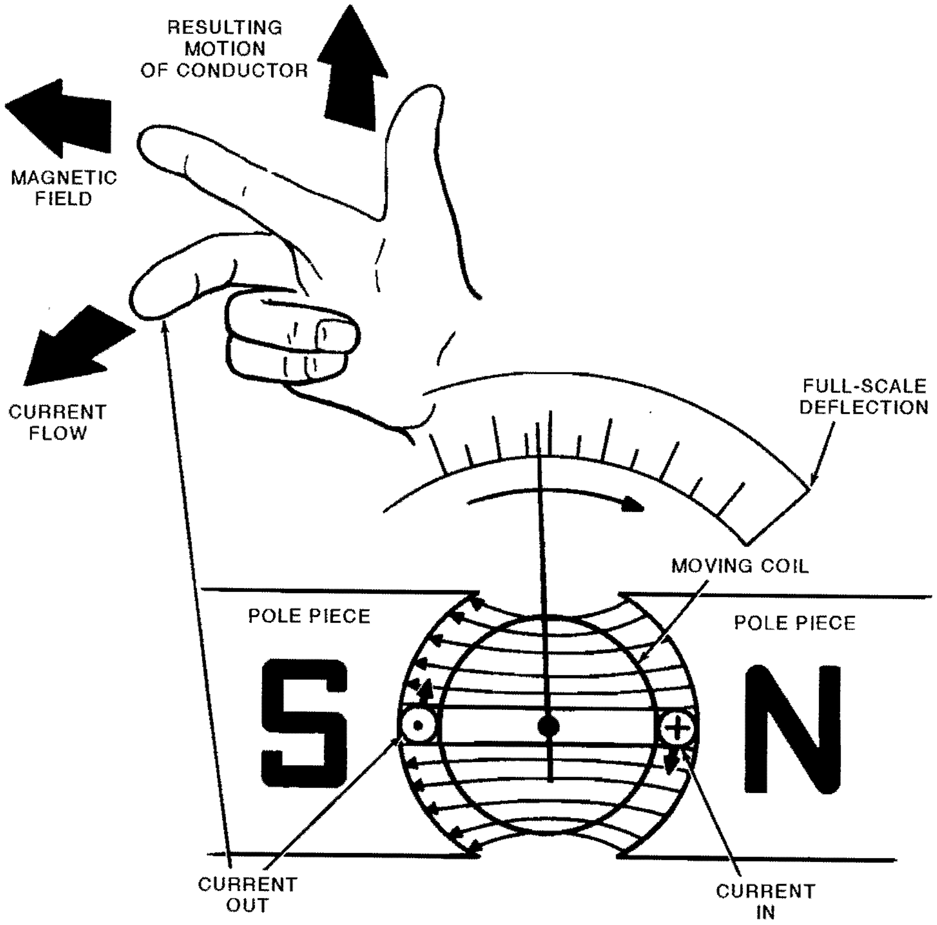
RESULTING MOTION OF CONDUCTOR
MAGNETIC FIELD
CURRENT FLOW
FULL-SCALE DEFLECTION
MOVING COIL
POLE PIECE
POLE PIECE
S
N
CURRENT OUT
CURRENT IN

Figure 6-5
Motor action of the moving coil.

The amount of torque produced by this tiny "motor" is proportional to the magnitude of the current which flows through the moving coil. The more current, the greater the torque and the further the pointer deflects.

Meter movements are rated by the amount of current required to produce a full-scale deflection. For example, a 50 microampere meter movement deflects full scale when only 50 microamperes of current flows through it. The 50 µA meter movement is one of the most commonly used types of d'Arsonval movements. The 100 µA and 200 µA movements are also popular. Figure 6-6 shows several different meter movements.

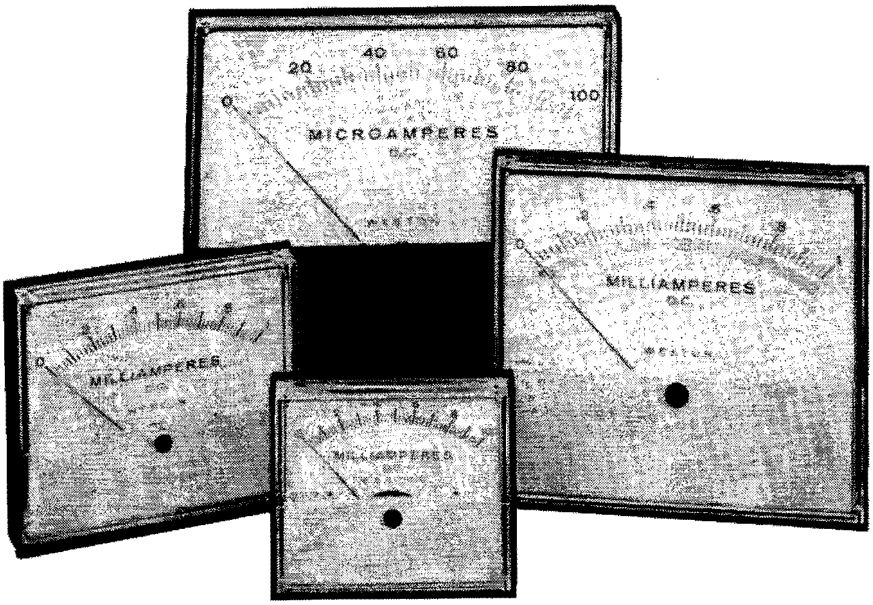

Figure 6-6

Meter movements come in different shapes, sizes, and sensitivities.
Courtesy Weston.

Figure 6-5 illustrates an important characteristic of the d'Arsonval meter movement. Assume that the current is always flowing in the same direction through the moving coil. That is, a direct current (DC) is applied to the coil. This movement works fine as long as the current is direct. However, the movement will not respond properly to alternating current (AC). Each time the current reverses, the coil attempts to reverse its direction of deflection. If the current changes direction more than a few times each second, the coil cannot follow the changes. Therefore, you must not apply AC to this type of meter movement.

Taut-Band Movement

An important variation of the d'Arsonval movement is the taut-band meter movement. Figure 6-7 is a simplified diagram which shows the construction of this type of movement. The moving coil is suspended by two tiny stretched metal bands. One end of each band connects to the moving coil while the other end connects to a tension spring. The purpose of these springs is to keep the bands pulled tight. The bands replace the pivots, bearings, and spiral springs in the conventional d'Arsonval movement. This not only simplifies the construction of the meter, it also reduces the friction to practically zero. Consequently, the taut-band movement is somewhat more sensitive than the movement described earlier. Taut-band instruments with 10 μA movements are available.

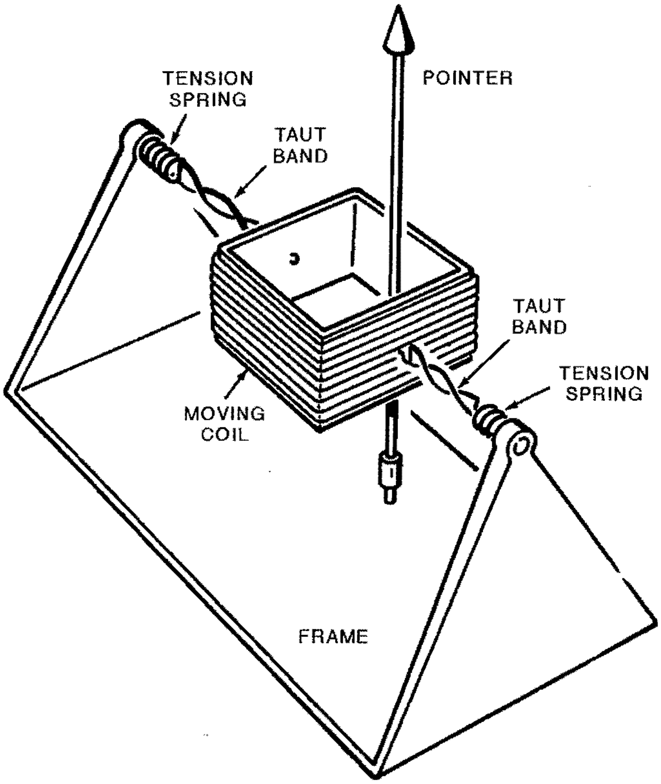

Figure 6-7
Taut-band meter movement.

The taut-bands serve several purposes. First, they suspend the coil in such a way that the friction is nearly zero. When current is applied, the coil rotates and the bands are twisted. When current is removed, the bands untwist returning the pointer to the zero position. The bands also serve as the current path to and from the coil.

The taut-band movement has several advantages over the original d'Arsonval type. As you have seen, it is generally more sensitive. It is also more rugged and durable. Mechanical shocks simply deflect the tension springs which can then bounce back to their original positions. The instrument remains more accurate for the same reason. Because of these advantages, the taut-band movement is most popular.

Programmed Review

1. The permanent-magnet, moving-coil meter movement is the type used in most general-purpose meters. This type of movement is often called the ____________ movement after its inventor.

2. (d'Arsonval) In this movement, a stationary magnetic field is provided by a ______________ ____________ .

3. (permanent magnet) Pole pieces and a soft-iron core concentrate the magnetic field in the air gap through which the ____________ ____________ rotates.

4. (moving coil) Attached to the coil is a ____________ which rotates in front of a scale.

5. (pointer) Two spiral springs return the pointer to the ____________ position when no current flows through the coil.

6. (zero) A rule which tells us which way the coil rotates is called the ____________-____________ motor rule.

7. (right-hand) This type of meter movement indicates properly only when the applied current is ________ .
DC/AC

8. (DC) A variation of the d'Arsonval movement uses thin metal bands to replace the pivots, jeweled bearings, and spiral springs. This type of meter movement is called the ____________-____________ type.

9. (taut-band) The taut-band movement has several advantages. For one thing it is generally more sensitive. This means that less ____________ is required to cause full scale deflection.

10. (current) It is also more rugged and durable.

THE AMMETER

The meter movements that were described in the previous section are basically current meters. That is, they deflect when current flows through them. In each case, the moving coil consists of many turns of extremely fine wire. Fragile spiral springs or the taut-bands of the movement carry current to the coil. Due to the delicate nature of the coil and the springs or bands, you must take care not to apply excessive current through the movement. The current necessary for full-scale deflection does not harm the movement, but a 100% overload might. The coil may burn out; the spring may be damaged; or the aluminum needle may become bent if it is driven too hard against the right retaining pin.

Also, you musty take care to observe polarity when you use the meter movement. A reverse current causes the needle to deflect backwards. If the current is too great, the needle may become bent when it bangs against the left retaining pin.

Measuring Current

The rules for using the ammeter were described earlier. Before you continue, review these rules.

First, you must connect the ammeter in series with the current to be measured. This means that you must break the circuit under test so that you can insert the ammeter. This is the prime disadvantage of the ammeter.

Second, you must observe polarity when you connect the meter. This simply means that you should connect the ammeter so that it deflects up scale. The terminals of meters are generally marked with – and +. Simply connect the meter so that current flows into the – terminal.

Third, you must not exceed the current ratings of the meter.

Increasing the Range of the Ammeter

Each meter movement has a certain current rating. This is, the current which causes full-scale deflection. For example, an inexpensive meter movement may have a current rating of 1 milliampere. To obtain a usable reading, the current through the movement cannot be more than 1 mA. By itself, the movement has a single usable range of 0 to 1 mA.

Obviously, the meter would be much more useful if it could measure currents greater than 1 mA, as well as those less than 1 mA. Fortunately, there is an easy way to convert a sensitive meter movement to a less sensitive current meter. To do this, you connect a small value resistor in parallel with the meter movement. This resistor is called a *shunt*. Its purpose is to act as a low resistance path around the movement so that most of the current flows through the shunt and only a small current flows through the movement.

Figure 6-8A illustrates a 1 mA meter movement that is connected across a low resistance shunt to form a higher range ammeter. The range depends on how much current flows through the shunt. In Figure 6-8B, the current that is applied to the ammeter is 10 mA. However, only 1 mA of this flows through the meter movement. The other 9 mA flows through the shunt. Thus, to convert the 1 mA movement to a 0-10 mA meter, you must choose the shunt so that 9/10 of the applied current flows through the shunt. After you do this, the full scale position on the scale indicates 10 mA because this is the amount of current that must be applied before the meter reaches full-scale deflection.

If you make the value of the shunt smaller, the meter will indicate even higher values of current. Figure 6-8C shows the requirements necessary to measure 100 mA. Here, 99 mA or 99 percent of the applied current must go through the shunt. Thus, the resistance of the shunt must be much smaller than the resistance of the meter movement.

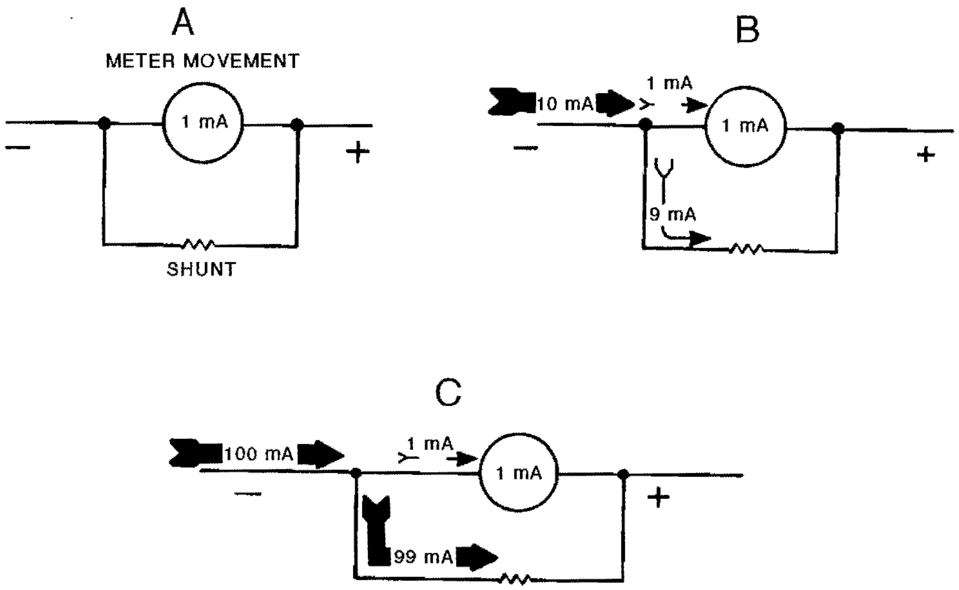

Figure 6-8
Increasing the current range of the ammeter.

Computing the Shunt Resistance

To determine the proper value of the shunt resistor, you must first know something about the characteristics of the meter movement. From the earlier example, you know that full scale deflection requires 1 mA. However, you must also know either the resistance of the meter movement or the voltage that is dropped by the movement when the current is 1 mA. Of course, if you know one, you can compute the other.

You can find the resistance value of the meter movement in the manufacturer's literature, catalog, or operating instructions. Often, it is printed right on the meter movement itself. Assume that the 0-1 mA movement has a resistance of 1000 ohms or 1 kilohm. In this case, 1 mA of current causes a voltage drop across the meter movement of:

$$E = IR$$

$$E = 1\text{ mA} \times 1\text{ k}\Omega$$

$$E = .001\text{ A} \times 1000\ \Omega$$

$$E = 1\text{ volt}$$

If you refer back to Figure 6-8, you see that this voltage is developed across the meter movement in each of the examples shown. Since the shunt resistance is connected in parallel with the meter movement, this same voltage is developed across the shunt. This means that in the example shown in Figure 6-8B, the 9 mA current develops 1 V across the shunt. You can use Ohm's Law to compute the value of the shunt since you now know the current and voltage. Thus, the value of the shunt should be:

$$R = \frac{E}{I}$$

$$R = \frac{1\text{ V}}{9\text{ mA}}$$

$$R = \frac{1\text{ V}}{.009\text{ A}}$$

$$R = 111\text{ ohms}$$

This is the resistance necessary to shunt 9 mA around the meter when a current of 10 mA flows in the circuit. However, the shunt works equally well when the movement indicates half-scale or 0.5 mA. Again, you can use Ohm's Law to calculate the voltage across the meter:

$$E = IR$$

$$E = 0.5\text{ mA} \times 1\text{ k}\Omega$$

$$E = 0.0005\text{ A} \times 1000\ \Omega$$

$$E = 0.5\text{ volt}$$

Since the voltage across the meter and the 111 ohm resistor are the same, the current through the shunt is:

$$I = \frac{E}{R}$$

$$I = \frac{0.5\ \text{V}}{111\ \Omega}$$

$$I = .0045\ \text{A or } 4.5\ \text{mA}$$

As you can see, nine-tenths of the current still flows through the shunt while only one-tenth flows through the movement. Thus, the movement indicates 0.5 mA when 5 mA of current flows in the circuit. The meter scale is marked off 0 through 10 instead of 0 through 1, and a 111 ohm resistor is connected across the meter movement. This converts the circuit to a 0-10 mA current meter.

Interestingly enough, there is another way you can find the value of the shunt. Refer to Figure 6-8B again. You know that 9 mA must flow through the shunt so that the remaining 1 mA flows through the meter movement. In order for the shunt to conduct 9 times as much current as the meter, its resistance must be only 1/9 that of the meter resistance. Now since the meter resistance is 1000 ohms, the shunt resistance must be $\frac{1000\ \Omega}{9}$ or 111 ohms.

Try to apply these two methods to the situation shown in Figure 6-8C. Once again the current through the meter movement is 1 mA. Thus, the voltage drop across the movement and across the shunt is still 1 volt. This allows you to compute the value of the shunt:

$$R = \frac{E}{I}$$

$$R = \frac{1\ \text{V}}{99\ \text{mA}}$$

$$R = \frac{1\ \text{V}}{.099\ \text{A}}$$

$$R = 10.1\ \text{ohms}$$

You arrive at this same answer by reasoning that the shunt resistance must be 1/99 that of the meter resistance, since the shunt conducts 99 times as much current. Therefore, the shunt resistance must be:

$$\frac{1000\ \Omega}{99} = 10.1\ \text{ohms}$$

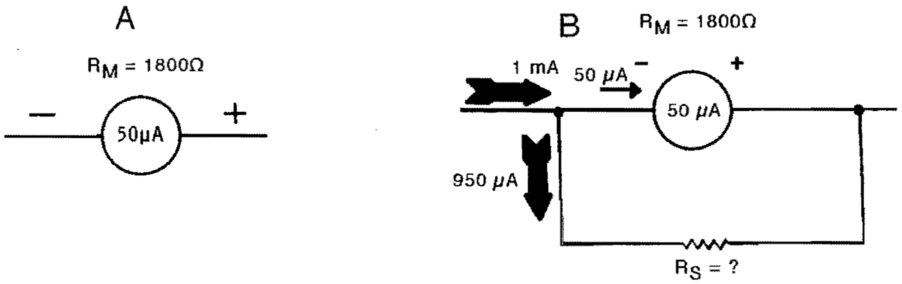

Figure 6-9

Find the value of R_S.

Now try another example. Figure 6-9A shows a 0-50 μA meter movement with a resistance of 1800 ohms. What value shunt is required to construct a 0-1 mA meter? Figure 6-89B shows the current distribution. Notice that 1 mA or 1000 μA of current flows through the circuit. However, only 50 μA can flow through the meter movement. The remaining 950 μA must flow through the shunt. Since you know the resistance of the meter movement (1800 Ω) and the current through it (50 μA), you can compute the voltage across it:

$$E = IR$$

$$E = 50\ \mu\text{A} \times 1800\ \Omega$$

$$E = 0.00005\ \text{A} \times 1800\ \Omega$$

$$E = 0.09\ \text{volts}$$

Because the shunt is in parallel with the meter movement, this same voltage is developed across the shunt. Thus, you can compute the shunt value:

$$R_s = \frac{E}{I}$$

$$R_s = \frac{0.09\ \text{V}}{950\ \mu\text{A}}$$

$$R_s = \frac{0.09\ \text{V}}{0.00095\ \text{A}}$$

$$R_s = 94.7\ \Omega$$

As before, you can arrive at this same answer by reasoning that 95% of the current flows through the shunt. This means that 95% or 19 times as much current flows through the shunt as through the meter movement. Because the shunt conducts 19 times as much current, the resistance of the shunt must be 1/19 that of the meter movement. Thus, the shunt resistance must be:

$$\frac{1800\ \Omega}{19} = 94.7\ \Omega$$

Ammeter Accuracy

Every meter movement has a certain accuracy associated with it. The accuracy is specified as a *percentage of error at full-scale deflection.* Accuracies of ±2% or ±3% of full-scale are common for good-quality instruments. Figure 6-10 illustrates what ±3% of full scale means. The scale shown is a 100 mA current scale. Remember, the meter accuracy refers to full-scale deflection. At full scale, ±3% equals ±3 mA. For this meter, a current of exactly 100 mA could cause the meter to read anywhere from 97 mA to 103 mA. Another way to look at it is that a meter reading of exactly 100 mA might be caused by an actual current between 97 mA to 103 mA.

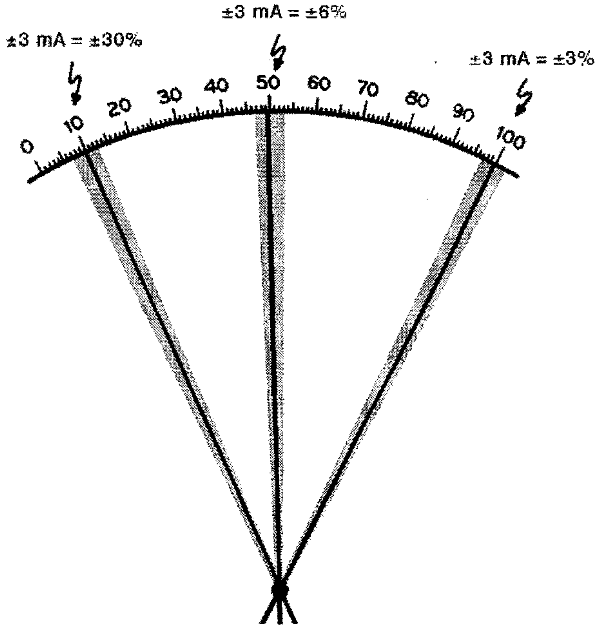

Figure 6-10
Meter accuracy of ±3%.

As you can see a, ±3% accuracy means that the reading may be off by as much as ±3 mA at full-scale. More importantly, it means that the reading may be off by as much as ±3 mA at any point on the scale. For example, when the meter indicates 50 mA, the actual current may be anywhere from 47 mA to 53 mA. Thus, at half-scale the accuracy is no longer ±3%; it is now ±6%. By the same token, for an indicated current of 10 mA the actual current may be anywhere from 7 mA to 13 mA. Here, the accuracy is only ±30%.

Because meter accuracy is specified in this manner, the accuracy gets progressively worse as you move down the scale. For this reason, current measurements are most accurate when you select a current range that causes near full-scale deflection of the meter. The nearer full scale, the more accurate the reading.

Programmed Review

11. The ammeter is a device that measures ____________ .

12. (current) Because many current meters measure currents less than 1 ampere, they are often called ____________ ammeters or ____________ ammeters.

13. (milliammeters, microammeters) You must always connect an ammeter in ____________ with the circuit under test.

14. (series) Also, you must observe ____________ when you insert an ammeter into a circuit.

15. (polarity) Each meter movement has a certain full-scale current rating. However, you can place a resistor in parallel with the meter movement to extend the current range of the instrument. This parallel resistor is called a ____________ .

16. (shunt) For example, a shunt could be added to the meter movement shown in Figure 6-9A to extend the range to 10 mA. The first step you need to do to compute the shunt value is determine the voltage drop across the meter movement when the current through it is 50 µA. To do this, you can use the formula: ____________ .

17. ($E = IR$) With this formula, you find that the voltage drop is _________ .

18. (0.09 volts) Because the shunt is in parallel with the meter, the same voltage is developed across the shunt. Thus, if you know the current through the shunt, you can compute the required resistance value. Since 10 mA is applied to the meter and shunt, and only 50 µA flows through the meter, the remaining current through the shunt must be: 10 mA – 50 µA = ____________ mA.

19. (9.950 mA) You now know the current through the shunt (9.950 mA) and the voltage that is developed across it (0.09 volts). Therefore, you can use the formula: ____________ to compute the resistance.

20. ($R = \frac{E}{I}$). With this formula, you find that the proper value of the shunt is ____________ ohms.

21. (9.045 ohms) The accuracy of an ammeter refers to the percentage of error at ____________-____________ deflection.

22. (full-scale) A 100 mA ammeter with an accuracy of ± 2% of full scale reads within ±____________ mA of the actual current at any point on the scale.

23. (± 2 mA) Thus, a reading of 50 mA is caused by a current between ____________ mA and ____________ mA

24. (48 mA, 52 mA) Consequently, at 50 mA, the accuracy of the meter is not ±2% but ± __________%.

25. (±4%)

THE VOLTMETER

You can use the basic meter movement to measure voltage as well as current. In fact, every meter movement has a certain voltage rating as well as a current rating. This is the voltage which causes full scale deflection. Of course, the voltage rating is actually determined by the current rating and the meter resistance. For example, a 50 µA meter movement which has a resistance of 2000 Ω deflects full scale when it is connected across a voltage of:

$$E = IR$$

$$E = 50\ \mu A \times 2000\ \Omega$$

$$E = 0.1 \text{ volt}$$

That is, the meter movement alone could be used to measure voltages up to 0.1 volt. Thus, the meter scale is calibrated from 0 to 0.1 volt. However, if the meter movement is connected across a much higher voltage such as 10 volts, it may become damaged. Obviously, to be practical, you must extend the voltage range of the basic meter movement.

Extending the Range

You have seen that a 50 µA, 2000-ohm meter movement can withstand a voltage of 0.1 volt without exceeding full scale. To extend the range, you must make sure that the voltage across the meter does not exceed 0.1 volt when the meter movement is connected across a higher voltage. You do this by connecting a resistor in *series* with the meter movement as shown in Figure 6-11. The resistor is called a *multiplier* because it multiplies the range of the meter movement.

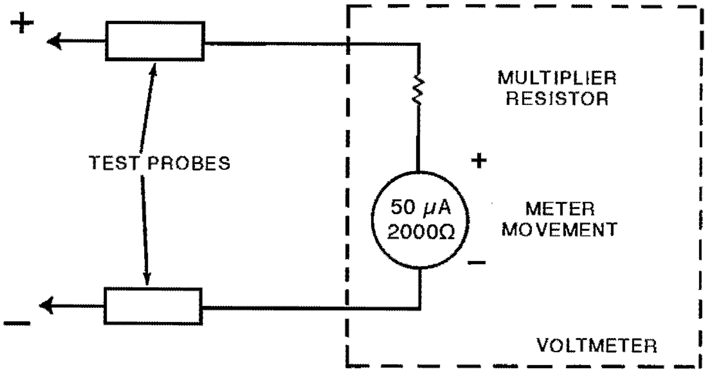

Figure 6-11
A voltmeter is formed by connecting a multiplier resistor in series with a microammeter.

The purpose of the multiplier resistor is to limit the current which flows through the meter movement. For example, in the voltmeter shown in Figure 6-10, the current through the meter movement must be limited to 50 μA. Another way to look at it is that the multiplier must drop all the voltage applied to the voltmeter except the 0.1 volt allowed across the meter movement. For example, if the range is to be extended to 10 volts, then the multiplier must drop 10 V – 0.1 V = 9.9 volts.

Figure 6-12 shows a voltmeter that contains a very large multiplier resistor so it can measure voltages up to 40,000 volts.

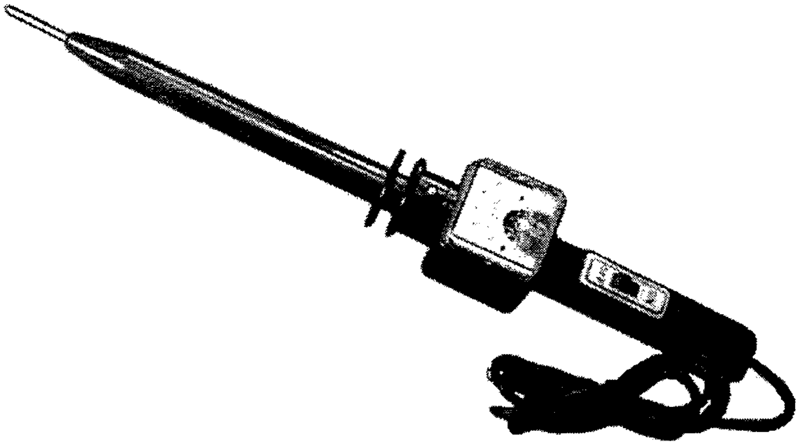

Figure 6-12

This single range voltmeter can measure voltages up to 40,000 volts.

Calculating the Multiplier

You have seen that the value of the multiplier must be high enough to limit the current to the full-scale current rating of the meter movement for any applied voltage. If you keep this in mind, you can easily calculate the required value of the multiplier for any voltage range.

Assume you wish to convert the 50 μA, 2000-ohm meter movement to a 10-volt voltmeter by adding a multiplier in series. Obviously, a current of only 50 μA must flow when the voltmeter is connected across 10 volts. Thus, the total resistance of the voltmeter must be:

$$R_{total} = \frac{E_{full\text{-}scale}}{I_{full\text{-}scale}}$$

$$R_{total} = \frac{10\ V}{50\ \mu A}$$

$$R\ total = 200{,}000\ \Omega$$

However, the meter movement itself has a resistance of 2000 ohms. Thus, the multiplier must have a value of 200,000 Ω – 2000 Ω = 198,000 Ω or 198 kΩ.

This means that the basic 50 µA, 2000 Ω meter movement can now measure 0 to 10 volts because 10 volts causes a full-scale deflection. From a voltage standpoint, the multiplier resistor drops 99% of the applied voltage. That is, for an applied voltage of 10 volts, the multiplier drops:

$$E = IR$$

$$E = 50\,\mu\text{A} \times 198{,}000\,\Omega$$

$$E = 9.9 \text{ volts}$$

This leaves 0.1 volt across the meter. Because, the total voltmeter resistance is 100 times larger than the meter resistance, the range of the meter is multiplied by 100. Of course, the meter scale should now be calibrated from 0 to 10 volts.

To be sure you have the idea, determine the value of multiplier that is required to convert the same meter movement to a 0-100 volt voltmeter. This time, the multiplier must limit the current to 50 µA when 100 volts is applied. Thus, the total resistance of the voltmeter must be:

$$R_{\text{total}} = \frac{E_{\text{full-scale}}}{I_{\text{full-scale}}}$$

$$R_{\text{total}} = \frac{100\text{ V}}{50\,\mu\text{A}}$$

$$R \text{ total} = 2{,}000{,}000 \text{ ohms or } 2\text{ M}\Omega$$

Here again, 2000 ohms are supplied by the meter movement. Thus, the value of the multiplier must be:

$$R_{\text{multiplier}} = R_{total} - R_{meter}$$

$$R_{\text{multiplier}} = 2{,}000{,}000\,\Omega - 2000\,\Omega$$

$$R_{\text{multiplier}} = 1{,}998{,}000\,\Omega - 1.998\text{ M}\Omega$$

Notice that 1.998 MΩ is extremely close to 2 MΩ. The difference is so slight that you probably would not notice any difference in deflection regardless of which value you use. In this case, you would probably use a standard value 2 MΩ resistor instead of the 1.998 MΩ value which is not easy to obtain.

Multiple-Range Voltmeters

A practical voltmeter has several ranges. Figure 6-13 shows one arrangement for achieving multiple ranges. Here, the voltmeter has four ranges which are selected by the range switch. Again, the 50 µA, 2000 Ω meter-movement is used. On the 0.1-volt range no multiplier is required since this is the voltage rating of the meter movement itself.

On the 1-volt range, R1 is switched in series with the meter movement. The value of R_1 is given as 18 kΩ. You can use the procedure outlined earlier to verify that this is the proper value multiplier required.

Notice that on the 10-volt and 100-volt ranges, the multiplier values you computed earlier are switched in series with the meter movement.

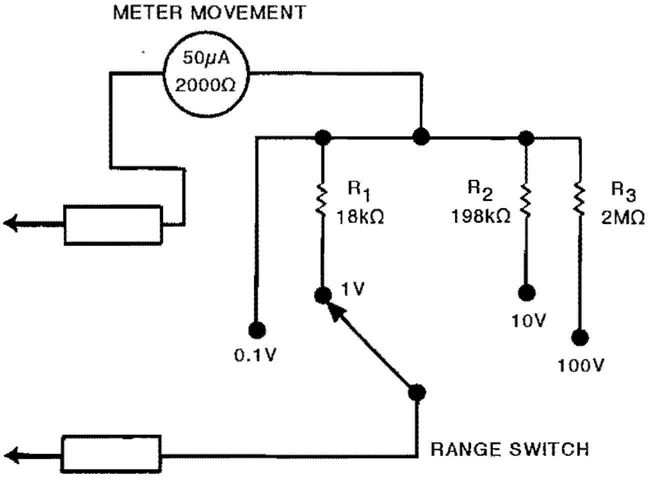

Figure 6-13
Multirange voltmeter.

Figure 6-14 shows another arrangement that is sometimes used when several ranges are required. On the 0.1-volt range, no multiplier is required. On the 1-volt range, an 18 kΩ multiplier is switched in series with the meter movement. Up to this point, the arrangement is similar to that shown in Figure 6-13, but this is where the similarity ends. On the 10-Volt range, R_2 is switched in series with R_1. Thus, the total resistance in series with the meter movement is 18 kΩ + 180 kΩ = 198 kΩ. Notice that this is the same value of multiplier that is used on the 10-volt range in Figure 6-13. The only difference is that in Figure 6-13 a single 198 kΩ resistor is used, while in Figure 6-14 two resistors having a total resistance of 198 kΩ are used.

On the 100-volt range, R_3 is switched in series with R_1 and R_2. Thus, the total multiplier resistance is 18 kΩ + 180 kΩ + 1.8 MΩ = 1.998 MΩ. Recall that this is the exact multiplier value that you computed earlier for the 100-volt range.

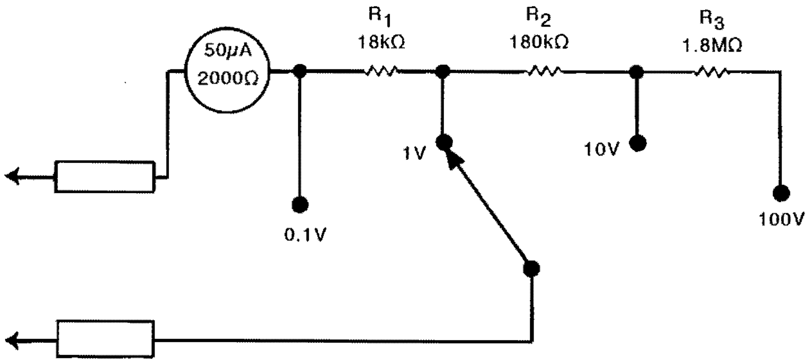

Figure 6-14
Here, the multiplier resistors are connected in series.

Sensitivity (Ohms-per-Volt)

An important characteristic of a voltmeter is its *sensitivity.* You can think of sensitivity as the amount of current that is required to produce a full-scale deflection of the meter movement. For example, a 50 μA meter movement is more sensitive than a 1 mA meter movement because less current is required to produce a full-scale deflection.

However, sensitivity is more often defined in another way. Sensitivity is normally expressed in ohms-per-volt (also written ohm/volt). The more sensitive the meter is, the higher the ohms-per-volt rating. You can divide the full-scale current rating of the meter movement into 1 volt to determine the sensitivity in ohms-per-volt of any voltmeter. That is:

$$\text{Sensitivity} = \frac{1 \text{ volt}}{I_{\text{full-scale}}}$$

Thus, the sensitivity of a voltmeter which uses a 50 μA meter movement is:

$$\text{Sensitivity} = \frac{1 \text{ volt}}{I_{\text{full-scale}}}$$

$$\text{Sensitivity} = \frac{1 \text{ volt}}{50\ \mu\text{A}}$$

$$\text{Sensitivity} = 20{,}000 \text{ ohms-per-volt}$$

This means that on the 1-volt range, the voltmeter has a total resistance of 20,000 ohms. You can refer back to Figure 6-13 or 6-14 to prove this. On the 1-volt range, the multiplier has a value of 18 kΩ and the meter movement has a resistance of 2 kΩ. Consequently, the total resistance is 20,000 ohms.

The full-scale current rating of the meter movement solely determines the sensitivity. Thus, it has the same sensitivity regardless of the range. Consequently, on any range, the voltmeters shown in Figure 6-13 and 6-14 have a resistance of 20,000 ohms x V, where V is the full-scale voltage of the range. Thus, on the 10 V range, the total voltmeter resistance is 20,000 ohms x 10 = 200,000 ohms.

Now try another example. What is the sensitivity of a voltmeter which uses a 1 mA meter movement? Remember, you determine sensitivity by dividing the full-scale current into 1 volt. That is:

$$\text{Sensitivity} = \frac{1\text{ volt}}{I_{\text{full-scale}}}$$

$$\text{Sensitivity} = \frac{1\text{ V}}{1\text{ mA}}$$

Sensitivity = 1000 ohms per volt

What would the total resistance of this voltmeter be on the 5-volt range? The resistance would be 1000 ohms x 5 = 5000 ohms.

Loading Effect of Voltmeters

An unfortunate aspect of electronics is that the act of measuring an electrical quantity often changes the quantity that you are attempting to measure. When you measure voltage, you must connect a voltmeter across the circuit under test. Since some current must flow through the voltmeter, the circuit behavior is modified somewhat. Often, you can ignore the effects of the voltmeter, especially if the meter has a high ohms/volt rating. However, if the voltmeter has a low ohms/volt rating, or the circuit under test has a high resistance, you cannot ignore the effects of the meter.

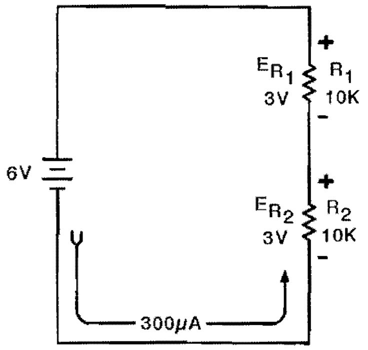

Figure 6-15
R_2 drops 3 volts.

Consider the circuit shown in Figure 6-13. Here, two 10 kΩ resistors are connected in series across a 6-volt battery. Since the resistors are the same value, each drops one half of the applied voltage or 3 volts. Thus, you would expect a voltmeter to read 3 volts if it were connected across either resistor. However, if the voltmeter has a low ohms/volt rating, the actual reading may be very inaccurate. Figure 6-16A shows the same circuit with a low-sensitivity voltmeter connected across R_2. The voltmeter has a sensitivity of 1000 ohms/volt. Since you expect the voltage across R_2 to be about 3 volts, the voltmeter is set to the 0-10 volt range. Thus, its resistance (R_m) is 1000 Ω x 10 = 10,000 Ω. Because R_m, is in parallel with R_2, the total resistance is reduced. As you learned in an earlier assignment, you can compute the parallel resistance (R_A) of the meter and R_2:

$$R_A = \frac{R_2 \times R_m}{R_2 + R_m}$$

$$R_A = \frac{10{,}000 \times 10{,}000}{10{,}000 + 10{,}000}$$

$$R_A = \frac{100{,}000{,}000}{20{,}000}$$

$$R_A = 5000\ \Omega \text{ or } 5\ \text{k}\Omega$$

Therefore, the circuit shown in Figure 6-16A reduces to the circuit shown in Figure 6-16B. Notice how this upsets the operation of the circuit. The total series resistance of R_1 and R_A is now only 15 kΩ instead of 20 kΩ, which allows more current to flow:

$$I = \frac{E}{R} = \frac{6\ \text{V}}{15{,}000\ \Omega} = 0.000400\ \text{A or } 400\ \mu\text{A}$$

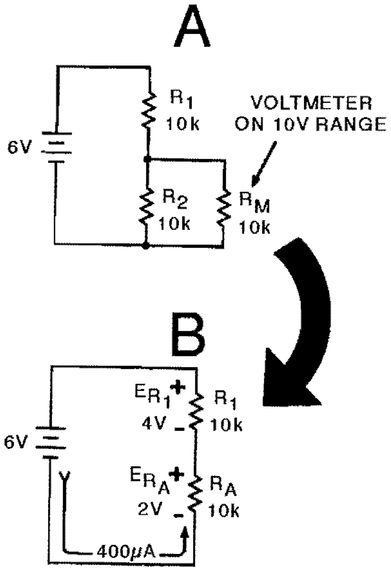

Figure 6-16
The 1000 ohms-per-volt meter loads down the circuit and causes an inaccurate reading.

Thus, the current increases from its previous value of 300 µA to a new value of 400 µA. The voltage distribution also changes because R_1 is now larger than R_A. The voltage dropped by R_A is:

$$E_{RA} = I \times R_A$$

$$E_{RA} = 0.0004\ \text{A} \times 5000\ \Omega$$

$$E_{RA} = 2\ \text{V}$$

The voltage dropped by R_1 increases to:

$$E_{R1} = I \times R_1$$

$$E_{R1} = 0.0004\ \text{A} \times 10{,}000\ \Omega$$

$$E_{R1} = 4\ \text{V}$$

Thus, instead of reading 3 volts as you would expect, the meter measures only 2 volts across R_2. This is an inaccuracy of 33%. This effect is called *loading.* The meter is loading down the circuit, which causes the voltage across R_2 to decrease. The loading effect becomes noticeable when the resistance of the meter approaches that of the resistor across which the meter is connected. For example, if the resistance of the meter were made 10 times that of R_2, the loading effect would be barely noticeable.

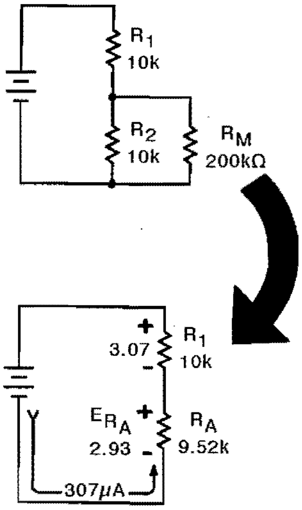

Figure 6-17

The 20,000 ohms-per-volt meter provides a much more accurate reading.

Figure 6-17 shows the same circuit with a 20,000 ohms/volt meter connected across R_2. On the 10-volt range, the resistance of the meter is 20,000 Ω x 10 = 200,000 Ω or 200 kΩ. Here, the equivalent resistance of R_m and R_2 in parallel is:

$$R_A = \frac{R_m \times R_2}{R_m + R_2}$$

$$R_A = \frac{200{,}000 \times 10{,}000}{200{,}000 + 10{,}000}$$

$$R_A = \frac{2{,}000{,}000{,}000}{210{,}000}$$

$$R_A = 9524\ \Omega \text{ or about } 9.52\ \text{k}\Omega$$

Notice that R_A is very close to the value of R_2. Therefore, the circuit operation is only slightly upset. The current increases only slightly to about:

$$I = \frac{E}{R} = \frac{6\ \text{V}}{10\ \text{k}\Omega + 9.52\ \text{k}\Omega} = \frac{6\ \text{V}}{19{,}520\ \Omega} = 0.000307\ \text{A or } 307\ \mu\text{A}$$

The voltage across R_1 rises to about:

$$E_{R1} = I \text{ x } R_1$$

$$E_{R1} = 0.000307\ \text{A x } 10{,}000\ \Omega$$

$$E_{R1} = 3.07 \text{ volts}$$

Meanwhile, the voltage across R_2 deceases slightly to:

$$E_{RA} = I \text{ x } R_A$$

$$E_{RA} = 0.000307\ \text{A x } 9{,}520\ \Omega$$

$$E_{RA} = 2.93\ \text{V}$$

Thus, instead of measuring 3 volts, the meter measures 2.93 volts. This inaccuracy is so small that you would probably never notice it. The loading effect is minimized when you use a voltmeter whose resistance is much higher than the resistance across which a voltage is to be measured.

Programmed Review

26. In the voltmeter, the you can extend the range by adding a resistor in ____________ with the meter movement.
parallel/series

27. (series) This resistor is called a ________________ resistor.

28. (multiplier) The purpose of the multiplier is to limit the current to the full-scale current rating of the ____________ ________________ .

29. (meter movement) Assume you wish to convert a 100 μA, 1000 Ω meter movement to a 10-volt voltmeter. In this case, a current of 100 μA should flow through the movement when the voltmeter is connected across ____________ volts.

30. (10) Thus, the total resistance of the voltmeter must be:

$$R_{total} = \frac{E_{full\text{-}scale}}{I_{full\text{-}scale}}$$

$$R_{total} = \frac{10\text{ V}}{100\ \mu\text{A}}$$

$$R_{total} = \underline{\qquad\qquad}\text{ ohms}$$

31. (100,000) Since the meter movement has a resistance of 1000 Ω, the value of the multiplier should be ____________ Ω.

32. (99,000) The sensitivity of this voltmeter is ____________ ohms-per-volt.

33. (10,000) The sensitivity or ohms-per-volt rating of a voltmeter is important because it determines the amount of ____________ effect the meter has on the circuit under test.

34. (loading) To minimize the loading effect, the ohms-per-volt rating should be as ____________ as possible.
high/low

35. (high)

THE OHMMETER

You can also use the basic meter movement to measure resistance. The resulting circuit is called an ohmmeter. In its most basic form, the ohmmeter is nothing more than a meter movement, a battery, and a series resistance.

Basic Circuit

Figure 6-18 shows the basic circuit of the ohmmeter. The idea behind the ohmmeter is to force a current to flow through an unknown resistance and then measure the current. For a given voltage, the current is determined by the unknown resistance. That is, the amount of current measured by the meter is an indication of the unknown resistance. Thus, the scale of the meter movement can be marked off in ohms.

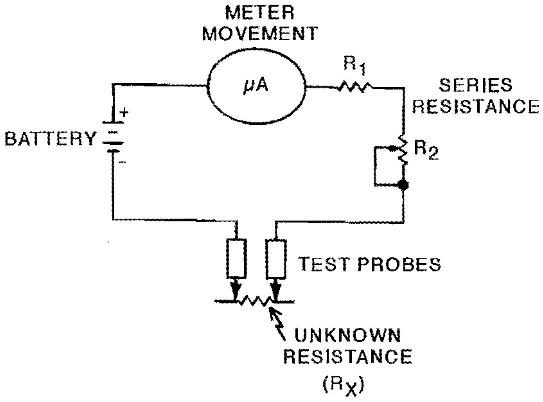

Figure 6-18
The circuit of a basic ohmmeter.

The purpose of the battery is to force current through the unknown resistance, and the meter movement measures the resulting current. The test probes have long leads and make your job of connecting the ohmmeter to the unknown resistor (R_x) simpler. Fixed resistor R_1 limits the current through the meter to a safe level. Variable resistor R_2 is called the ZERO OHMS adjustment. Its purpose is to compensate for battery aging.

Scale Calibration

In ohmmeters of this type, 0 ohms appears on the right side of the scale (at full-scale deflection). The reason for this is shown in Figure 6-19A. Here, the two test probes are shorted together. Thus, the unknown resistance (R_x) between the probes is equal to 0 ohms. In this case, the meter should deflect full scale to the 0 ohms marking of the scale. Full-scale deflection for this meter is 50 µA. In order for the 1.5 volt battery to force 50 µA of current through the circuit, the total circuit resistance must be:

$$R_T = \frac{E}{I}$$

$$R_T = \frac{1.5\ \text{V}}{.00005\ \text{A}}$$

$$R_T = 30{,}000\ \Omega$$

The meter provides 2000 ohms while R_1 provides 22,000 ohms. Thus, R_2 must be set to exactly 6,000 ohms to insure a current of exactly 50 µA.

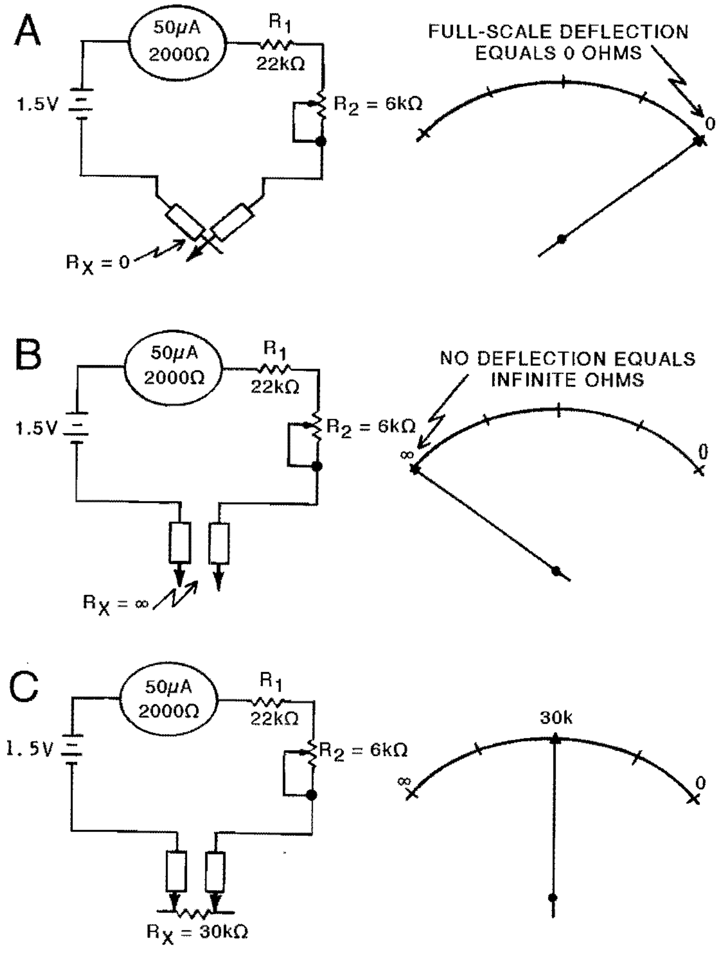
A
50µA
2000Ω
R1
22kΩ
1.5V
R2 = 6kΩ
Rx = 0
FULL-SCALE DEFLECTION EQUALS 0 OHMS
0
B
50µA
2000Ω
R1
22kΩ
1.5V
R2 = 6kΩ
Rx = ∞
NO DEFLECTION EQUALS INFINITE OHMS
∞
0
C
50µA
2000Ω
R1
22kΩ
1.5V
R2 = 6kΩ
Rx = 30kΩ
30k
∞
0

Figure 6-19
Calibrating the ends and center of the scale.

You may wonder why R_2 isn't a fixed 6,000 ohm resistor, or better yet, why R_1 isn't a fixed 28,000 ohm resistor. The reason for this is that the battery voltage changes as the battery discharges. If the battery voltage drops to 1.45 volts, to achieve full-scale deflection, the circuit resistance must be reset to :

$$R_T = \frac{E}{I}$$

$$R_T = \frac{1.45\ \text{V}}{.00005\ \text{A}}$$

$$R_T = 29{,}000\ \Omega$$

In this case R_2 would have to be reset to 5000 ohms to compensate for the lower voltage. R_2 is called ZERO OHMS adjust. The first step in every resistance measurement is to adjust this resistance to "zero the ohmmeter".

You have seen that a full-scale deflection corresponds to an unknown resistance, R_X, of 0 ohms. Thus, the scale is marked 0 at this point. Now, what about the left side of the scale (no deflection)? Figure 6-19B, on the previous page, illustrates this condition. Here, an open circuit exists between the two test probes. This corresponds to an infinite resistance. No current flows through the meter movement and the pointer rests at the left side of the scale. Consequently, this point on the scale is marked with the infinity symbol (∞). Thus, you have a scale with 0 ohms on the right and infinite ohms on the left.

Now, what resistance is represented by 1/2-scale deflection? The pointer will deflect to the center of the scale when the current is exactly 25 µA. This amount of current is caused by a total resistance of:

$$R_T = \frac{E}{I} = \frac{1.5\ \text{V}}{.000025\ \text{A}} = 60{,}000\ \Omega$$

Since the meter, R_1, and R_2 have a combined resistance of only 30,000 ohms, the unknown resistance R_X supplies the other 30,000 ohms. That is, the meter deflects to half scale (25 µA) when the unknown resistance has a value of 30 kΩ. Consequently, the 1/2-scale point is marked 30k as shown in Figure 6-19C.

You can use the same procedure to determine the amount of meter deflection for any value of R_X. Figure 6-20 illustrates that 1/3-full scale indicates an R_X of 60 kΩ, while *2/3-full scale indicates an R_X* of 15 kΩ. To verify this, observe that 1/3 of 50 µA or 16.66 µA flows in the circuit shown in Figure 6-20A. Also, verify that 2/3 of 50 µA or 33.33 µA flows in the circuit shown in Figure 6-20B.

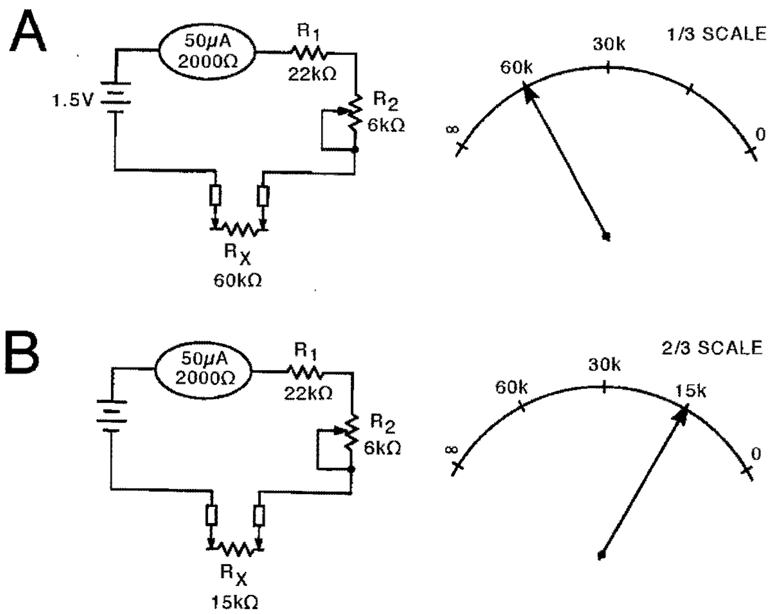
A
50μA
2000Ω
R1
22kΩ
1.5V
R2
6kΩ
Rx
60kΩ
60k
30k
1/3 SCALE
∞
0
B
50μA
2000Ω
R1
22kΩ
R2
6kΩ
Rx
15kΩ
60k
30k
2/3 SCALE
15k
∞
0

Figure 6-20
Calibrating for 1/3- and 2/3-scale deflection.

If you find enough points on the scale, the scale will take the form shown in Figure 6-21. There are two important differences between this scale and the ones used for current and voltage. First, the ohms scale is reversed with 0 on the right. Second, the scale is non-linear. For example, the entire upper half of the scale is devoted to a range of only 30 kΩ; that is, from 0 to 30 kΩ. However, notice that the second 30 kilohms (from 30 kΩ to 60 kΩ) takes up less than 1/4 of the scale. The markings are squeezed closer together on the left side of the scale. On ammeters and voltmeters the scale is linear. That is, the scale is marked off in equal increments of current or voltage.

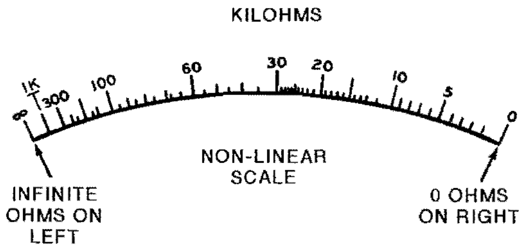
KILOHMS
∞
1K
300
100
60
30
20
10
5
0
NON-LINEAR SCALE
INFINITE OHMS ON LEFT
0 OHMS ON RIGHT

Figure 6-21
The ohmmeter scale.

Creating Higher Ranges

A single-range ohmmeter would not be very useful. For this reason, multi-range ohmmeters have been developed. Two techniques have evolved for creating additional ranges. Both techniques are used in some ohmmeters.

Figure 6-22 shows how you can implement a higher resistance range. First, you add a switch so you can choose between the two ranges. Second, you add a higher voltage battery. Finally, a higher value series resistor is required. To increase the range by a factor of 10, both the voltage and the total series resistance must be increased by a factor of 10.

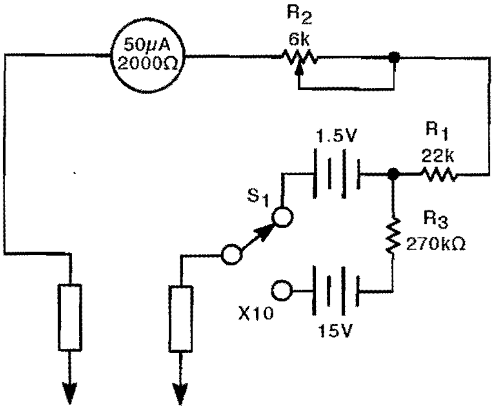

Figure 6-22
Creating higher resistance ranges.

When S_1 is in the position shown, the meter operates exactly like the one shown earlier in Figure 6-19 and 6-20. However, when S_1 is set to the x 10 position, the 1-volt battery is in series with R_3, R_1, R_2, and the meter. The higher voltage does not cause excessive current through the meter because the series resistance has been increased by the addition of R_3. Notice that the total resistance in the circuit is now 300 kΩ. Thus, when you short the leads together, the current is still:

$$I = \frac{E}{R} = \frac{15\text{ V}}{300\text{ k}\Omega} = 50\ \mu\text{A}$$

The right side of the scale still represents 0 ohms. However, half-scale deflection (25 μA) now occurs when the total resistance is:

$$R_T = \frac{15\text{ V}}{25\ \mu\text{A}} = 600\text{ k}\Omega$$

Of this meter, R_1, R_2, and R_3 supply 300 kΩ. Therefore, the unknown resistance R_X must be 300 kΩ. This means that the center of the ohmmeter scale now represents 300 kΩ instead of 30 kΩ. The range has been increased by a factor of 10.

Of course, you cannot carry this technique much further because if you increase the range by an additional factor of 10, you would require a 150-volt battery. Fortunately, the range described above is sufficient for general purpose use. It can measure resistance values up to several megohms. Resistors larger than this are rarely used in most electronic applications.

Creating Lower Ranges

You can also modify the basic ohmmeter to measure lower values of resistance. To do this, you switch a small value shunt resistor in parallel with the meter and its series resistance.

Refer to Figure 6-23. When switch S_1 is in the position shown, the ohmmeter operates exactly like the one shown earlier in Figure 6-19. However, when you change the position of S_1, R_3 is connected in parallel with the series combination of the meter, R_1 and R_2. The value of R_3 is 300 Ω or 1 percent of the combined series resistance of R_1, R_2 and the meter (30,000 Ω). Therefore, 99 percent of the current flows through R_3 and only 1 percent flows through the meter circuit. Recall that 25 μA of current is required for half-scale deflection of the meter. Determine what value of R_X will cause this amount of current to flow through the meter.

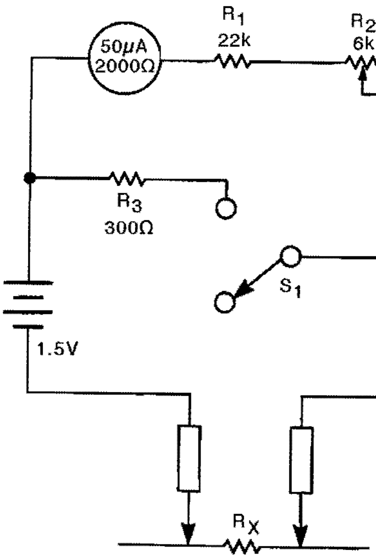

Figure 6-23
Creating lower resistance ranges.

The resistance of the meter circuit is now about 300 ohms. If you connect an unknown resistance R_X of 300 ohms between the probes, the current from the battery becomes:

$$I = \frac{1.5\text{ V}}{600\ \Omega} = 2.5\text{ mA}$$

However, 99% of this current (2.475 mA) flows through R_3. Only 1% or 25 µA flows through the meter movement. Thus, a half-scale deflection now represents an unknown resistance of 300 ohms instead of 30 kΩ. You can use this technique to create lower ohmmeter ranges.

Shunt Ohmmeter

The ohmmeters that were described up to this point are called series ohmmeters because the unknown resistance is always placed in series with the meter movement. You can recognize a series ohmmeter by its "backwards" scale. That is, 0 ohms is on the right while infinite ohms is on the left.

Another type of ohmmeter is called a shunt ohmmeter. Figure 6-24 shows the basic circuit of the shunt ohmmeter. This instrument gets its name from the fact that you place the unknown resistance in parallel (shunt) with the meter movement. This completely changes the characteristics of the ohmmeter. For example, notice that when an open (infinite ohms) exists between the probes, 50 µA of current flows through the meter movement. This produces a full-scale deflection. Consequently, infinite ohms is on the right side of the scale or at full-scale deflection. Note that this is just the opposite of the series ohmmeter.

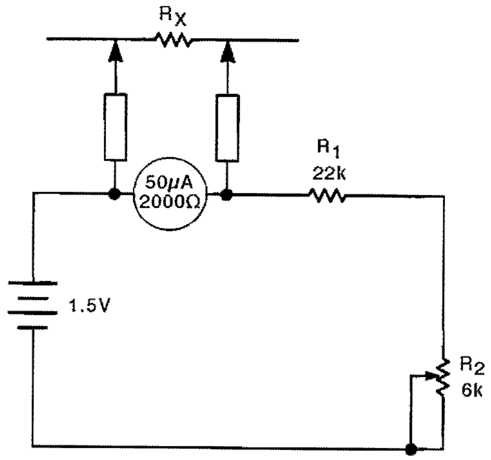

Figure 6-24
The shunt ohmmeter.

When you short together the probes on the shunt ohmmeter together (which represents an R_x of 0 ohms), the meter movement is shorted out. This produces no deflection. Thus, 0 ohms is on the left.

Recall that with the series ohmmeter, the half-scale reading was 30,000 ohms for the 50 µA, 2000 Ω meter movement. However, with the shunt ohmmeter, this too is different. Here, 25 µA of current flows through the meter movement when R_x is the same resistance as the meter movement. Thus, half-scale deflection on the shunt ohmmeter is marked 2000 ohms.

The shunt ohmmeter has some disadvantages. For one thing, the battery discharges any time the ohmmeter is turned on. This is not the case with the series ohmmeter. It draws current from the battery only when you measure a resistance or touch the leads together.

Also, the meter movement in the shunt ohmmeter is more easily damaged if you inadvertently connect the meter across a voltage source. In the series meter, the 28,000 ohms that is in series with the meter movement tends to limit the current. Even so, you should never connect either type of ohmmeter to a live circuit.

Finally, because the half-scale reading of the shunt ohmmeter is much less than that of the series ohmmeter, it is more difficult to accurately measure high resistance values on the shunt meter. However, it is easier to read low resistance values on the shunt meter for the same reason.

Programmed Review

36. A device for measuring resistance is called an ___________ .

37. (ohmmeter) In its most basic form, the ohmmeter consists of a ___________ ___________, a ___________, and a resistance connected in series.

38. (meter movement, battery) Generally, the series resistance consists of two parts: a fixed resistor which limits the current through the meter to a safe value and a variable resistor called the ___________ ___________ adjust.

39. (zero ohms) Its purpose is to compensate for different values of ___________ voltage.

40. (battery) In the series ohmmeter, 0 appears on the ___________ side of the scale.

41. (right) Assume that a 100 µA meter movement and a 9 volt battery are used in a series ohmmeter circuit. When you short the leads together, the meter should read 0 ohms or full-scale deflection. At this time, the total resistance in the circuit is ___________ ohms.

42. (90,000 ohms) You can use Ohm's Law to determine this:

$$R = \frac{E}{I} = \frac{9\text{ V}}{100\ \mu\text{A}} = \frac{9\text{ V}}{.0001\text{ A}} = 90{,}000\text{ ohms.}$$

This is the resistance provided by the meter movement, the fixed series resistance, and the zero ohms adjustment. What value of unknown resistance R_X causes a half-scale deflection? ___________

43. (90,000 ohms) Half-scale deflection is caused by 50 µA. Thus, the total series resistance is:

$$R = \frac{E}{I} = \frac{9\text{ V}}{50\ \mu\text{A}} = \frac{9\text{ V}}{.00005\text{ A}} = 180{,}000\text{ ohms.}$$

However, the meter circuit provides 90,000 ohms. Therefore, the size of R_x must be 90,000 ohms. Thus, the half-scale point on the meter scale should be marked ____________ ohms.

44. (90,000 ohms) With this type of ohmmeter, it would be somewhat impractical to create a higher resistance range since this would require a ____________-volt battery.

45. (90-volt) However, you could easily convert it to a lower resistance range simply by connecting a small-value resistor in ____________ with the meter and series resistance.

46. (parallel) With the proper value of shunt, the half-scale point can indicate 900 ohms instead of 90,000 ohms. To do this, you choose a value of shunt that will conduct ____________ % of the current in the circuit.

47. (99%) Thus a value of approximately ____________ ohms is required for the shunt.

48. (900 ohms) You should never connect an ohmmeter, no matter what type, to a ____________ ____________ .

49. (live circuit) This could damage the meter.

MULTIMETERS

Generally, the voltmeter, current meter, and ohmmeter are combined into a single instrument called a multimeter. There are several reasons for this. First, it is much easier to carry a single instrument than it is to carry three separate meters. Second, because only a single meter movement, case, set of test leads, etc., are required, it is much cheaper to buy a single multimeter than to buy three separate single-function meters.

Basic Circuit

A schematic diagram of a very basic multimeter is shown in Figure 6-25. This meter has three DC voltage ranges, two ohmmeter ranges, and three current ranges. Function switch S_2 determines if the multimeter acts as an ammeter, a voltmeter, or an ohmmeter. Range switch S_1 determines the range of the meter.

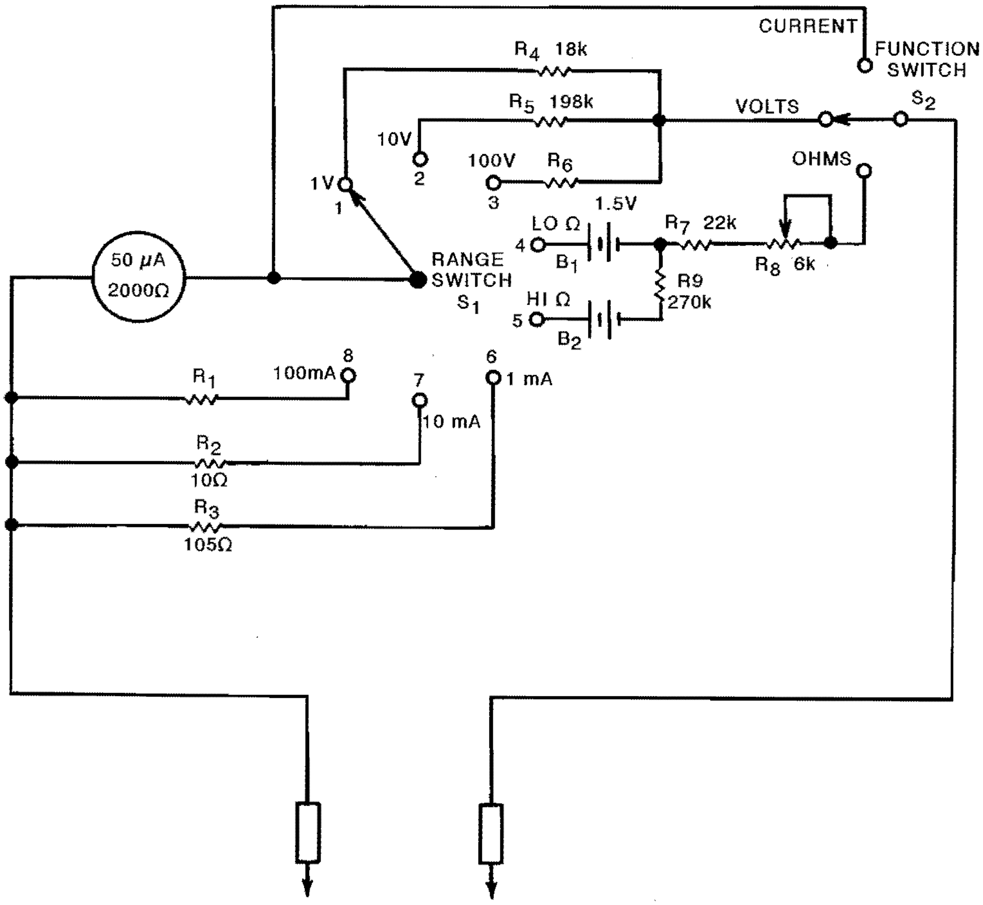
CURRENT
FUNCTION SWITCH
S2
VOLTS
OHMS
R4 18k
R5 198k
10V
2
100V R6
3
1V
1
1.5V
LO Ω
4
B1
R7 22k
R8 6k
R9 270k
HI Ω
5
B2
RANGE SWITCH
S1
50 µA
2000Ω
8
100mA
7
10 mA
6
1 mA
R1
R2
10Ω
R3
105Ω

Figure 6-25
The multimeter.

When you use the multimeter as a voltmeter, place S_2 in the VOLTS position and S_1 in one of the voltage positions (1 V, 10 V, or 100 V). As the circuit is drawn, the multimeter is set up to measure DC voltages up to 1 volt. Compare the voltmeter section of this meter with the multirange voltmeter that was shown earlier in Figure 6-13. Notice that the two voltmeters are virtually identical.

The ohmmeter portion of the multimeter has only two ranges. On the LOΩ range, B_1 supplies the current which causes the meter to deflect when S_2 is in the OHMS position and a resistance is connected between the two test probes. In the HIΩ position a higher voltage battery and a larger value series resistor increase the resistance range. The ohmmeter portion of the multimeter is exactly like the two-range ohmmeter shown earlier in Figure 6-20.

When function switch S_2 is in the current position, the two test probes are connected directly to opposite ends of the meter movement. When range switch S_1 is set to one of the current ranges, a resistor is placed in parallel (shunt) with the meter movement. On the 1 mA range, 50 µA flows through the meter movement when 1 mA flows through the circuit under test. Thus, 950 µA flows through the shunt R_3. Since 19 times as much current flows through R_3 as through the meter movement, R_3's resistance must be 1/19th that of the meter movement.

$$R_3 = \frac{2000\ \Omega}{19} = 105\ \Omega$$

The same line of reasoning shows that the value of R_2 must be about 10 ohms.

Electronic Multimeter

All of the meters discussed up to this point are classified as electrical meters. They consist of a meter movement, precision resistors, and a battery for the ohmmeter. However, there is another family of meters called electronic meters. These contain electronic circuits which can amplify small voltages and currents. These instruments use devices such as integrated circuits, transistors, and vacuum tubes which have not yet been described. For this reason, their circuitry is described in this course. Generally, the electronic meter is used in the same way as the electrical meter. However, one important difference is that the electronic meter has a much higher resistance than the electrical meter. For example, a good electrical meter has a sensitivity of 20,000 ohms-per-volt. Thus, on the 10-volt range, its resistance is 20,000 Ω x 10 = 200 kΩ. By contrast, most electronic meters have a resistance of 10 or 11 megohms on all DC ranges. Consequently, the electronic multimeter has very little loading effect on most circuits. Figures 6-26 and 6-27 on the next page show an electrical meter and a digital voltmeter.

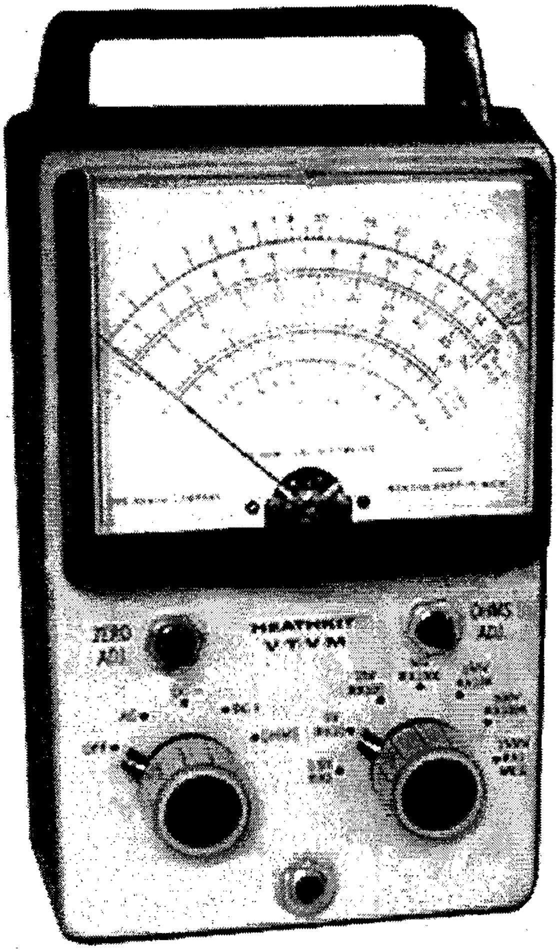
ZERO ADJ.
HEATHKIT
V.T.V.M
OHMS ADJ.
AC
DC
OHMS
OFF

Figure 6-26
It is not easy to tell an electrical meter from the electronic type.

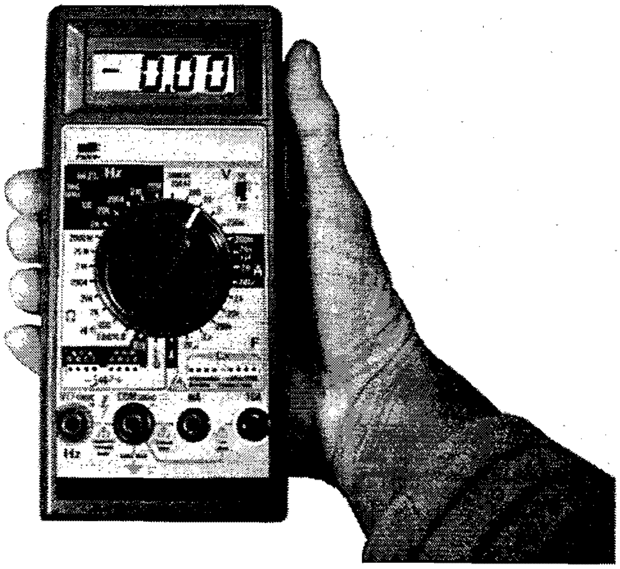

Figure 6-27
The digital voltmeter is easily recogized by its unique readout.

Measurement Inaccuracies

When you use a multimeter, there are several ways in which inaccuracies can slip into your measurements. Some of the causes of inaccurate measurements have already been described. Voltmeter loading is a good example. This error is minimized when you use a voltmeter which has a high resistance compared to the circuit resistances.

In somewhat the same way, the ammeter introduces an error when you use it to measure current. Since the ammeter has a finite value of resistance, it increases the overall circuit resistance when it is connected in series with the circuit. Of course, this reduces the current flowing in the circuit. As a result, the ammeter reads a value of current lower than the actual value without the meter. To minimize this error, you must use an ammeter with a very low value of resistance. The lower the ammeter resistance with respect to the circuit resistance, the smaller the error.

If you know the resistance value of the ammeter, you can take its loading effect into consideration and make a more accurate interpretation of the reading. Often the resistance of the ammeter is provided in the manufacturer's literature. If this value is not given, you can use the procedure shown in Figure 6-28 to determine the value. First, you set the ammeter to the desired scale; Next, you connect it in series with a variable resistor and a voltage source as shown in Figure 6-28. You then adjust R_1 for full-scale deflection of the meter. Variable resistor R_2 is now added to the circuit as shown in Figure 6-28B. You adjust it R_2 until the meter indicates exactly one half scale deflection. At this time, half of the current flows through R_2 and half flows through the meter. Thus, the resistance of R_2 must be equal to the resistance of the meter. Consequently, you can remove R_2 and measure the value of R_2 with the ohmmeter section of the multimeter to determine the resistance of the meter. You may wonder why you do not measure the resistance of the ammeter directly with an ohmmeter. On high current ranges, you can do this if a separate ohmmeter is available. However, when the ammeter is set to a low current range, the ohmmeter may produce enough current to harm the ammeter. Earlier, you saw that the resistance of a meter movement is an important factor when you design meter circuits. The can use the technique that was outlined above to determine the resistance of any meter movement as well as that of an ammeter.

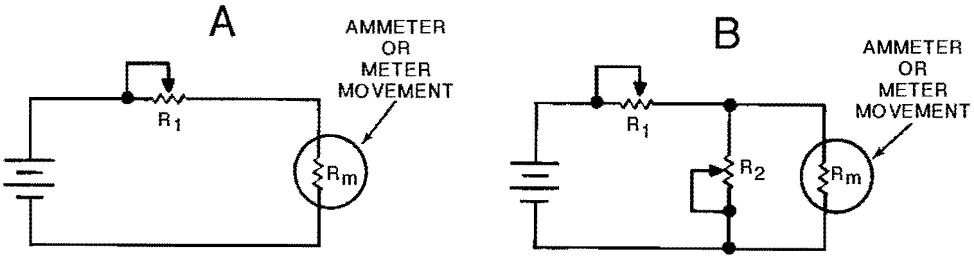

Figure 6-28

Finding the resistance of an ammeter or meter movement.

Aside from loading errors, the prime source of measurement inaccuracies is the characteristics of the meter itself. The meter movement may have an inaccuracy of ± 2% or ± 3% of full scale. Also, multiplier and shunt resistances may have a tolerance of 1%. When you add up these inaccuracies, a typical multimeter may have an overall accuracy of ± 3% to ± 4% for DC voltage and current ranges.

Another error which can creep into measurements is caused by improperly reading the meter. Parallax causes the most common error. Figure 6-29 illustrates parallax means. In Figure 6-29A, you are viewing the scale from directly in front of the meter. When you view the meter "straight on" like this, it indicates exactly 5 volts. If you move slightly to the right of the meter, the needle appears to point to the left of 5 volts as shown in Figure 6-29B. Also, if you view from the left of center, the needle appears to point to the right of 5 volts as shown in Figure 6-29C. Obviously then, for a correct reading, you should always read the scale "straight on" from directly in front of the meter. However, because you have two eyes, one eye will be to the right of center while the other will be to the left of center. To prevent errors in reading the meter, you should close one eye, and read the scale "straight on" with the other eye. Some meters have a mirror on the scale to help eliminate parallax errors. You close one eye and align the needle with the reflection of the needle in the mirror. This ensures that the open eye is directly in front of the needle.

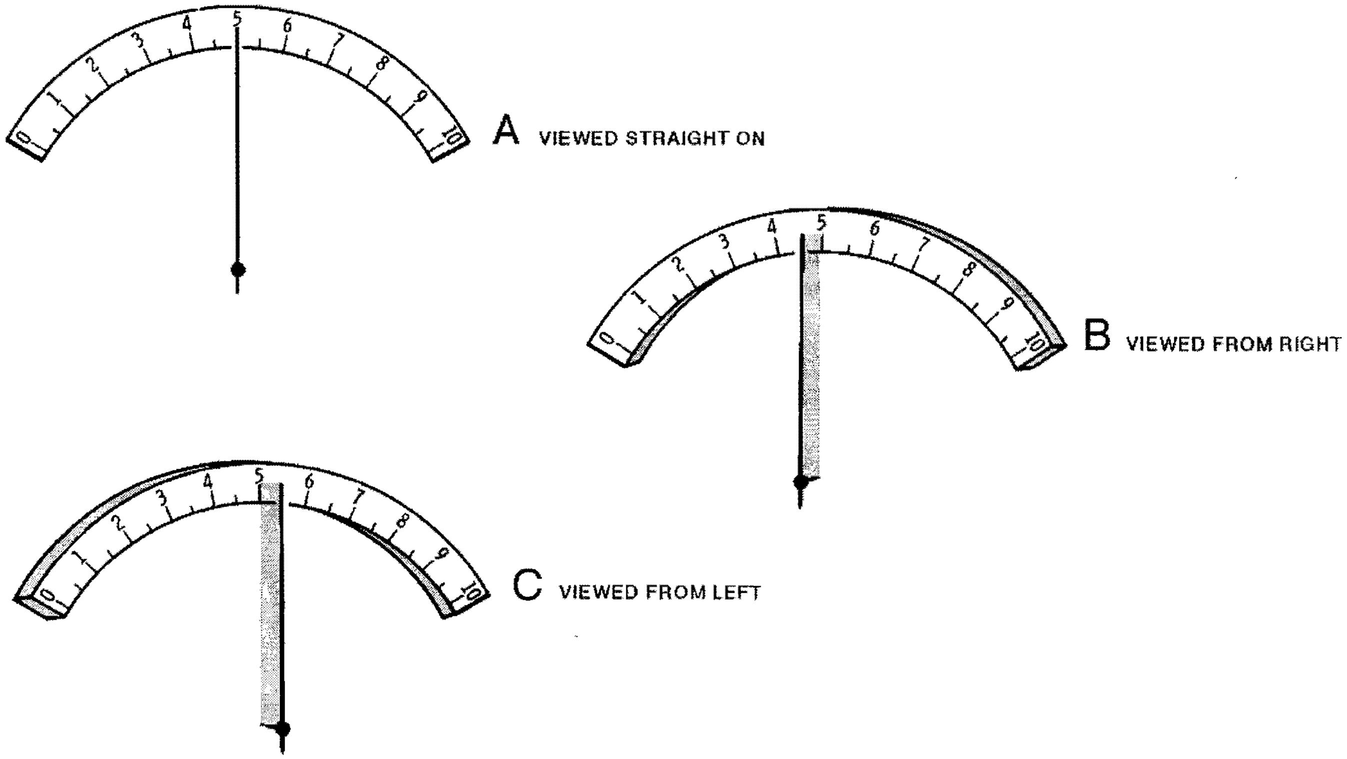

Figure 6-29

Parallax can cause errors.

Programmed Review

50. Generally, the voltmeter, ohmmeter, and current meter are combined in a single unit called a ____________ .

51. (multimeter) Figure 6-25 shows a very simple multimeter. R_4, R_5, and R_6 are used in the ____________ meter portion of the multimeter.

52. (voltmeter) These are called ____________ resistors.

53. (multiplier) R_7, R_8, R_9, and the two batteries are used in the meter portion of the multimeter.

54. (ohmmeter) R_8 is called the ____________ ____________ adjustment.

55. (zero ohms) R_1, R_2, and R_3 are used in the ____________ portion of the multimeter.

56. (milliammeter) These are called ____________ resistors.

57. (shunt) Some multimeters have integrated circuit, transistors, or vacuum tubes in addition to the meter movement circuits. These multimeters are called ____________ meters.

58. (electronic) The electronic meter has the advantage of a very __________ (low/high) resistance.

59. (high) This means that it generally has less ____________ effect than electrical meters.

60. (loading) Generally, the resistance is the same on all ranges and is often in the 10 MΩ range.

EXPERIMENT 15

Determining the Sensitivity of Your Voltmeter

OBJECTIVE: *To determine, by experimentation, the ohms-per-volt rating of your voltmeter.*

Introduction

The voltmeter you are using to perform these experiments may be either of two different types. It may be an analog VOM (electrical type meter) whose input resistance is different for each voltage range. That is, a 20,000 ohms-per-volt meter has a resistance of 20,000 ohms on a 1-volt range but 2,000,000 ohms on the 100-volt range. Or, it may be an electronic voltmeter (digital or bench-powered analog) which has a resistance of 10 or more megohms on all ranges. This experiment will tell you what type of meter you have and either its sensitivity in ohms-per-volt, or in the case of an electronic meter, its input resistance.

Material Required

1 — Heathkit Analog Trainer
1 — Voltmeter (multimeter) with test leads
1 — Separate analog ohmmeter
1 — 10 MΩ, 5% resistor, 1/2-watt (brown-black-blue-gold)
#22 copper wire

Procedure

1. The simplest way to determine the resistance of your voltmeter is to measure it directly with a separate ohmmeter. If you have two meters; for example an inexpensive electrical type, and an electronic (perhaps digital) type, complete steps 2 through 11. Use the electronic meter to measure the resistance of the other (non-electronic) meter, as described in steps 2-11. If you do not have two separate meters, go directly to step 12.

2. Set your voltmeter to one of the middle DC volts ranges.

3. If necessary, zero the ohmmeter.

4. Connect the ohmmeter across the voltmeter leads.

5. Record the resistance of the voltmeter. ____________ ohms

6. Set your voltmeter to the next higher DC volts range.

7. Record the resistance of the voltmeter. ____________ ohms

8. If the resistance readings recorded in steps 5 and 7 are very high and are the same in both cases, your voltmeter is one of the *electronic* types. To verify this, measure the resistance on other DC voltage ranges. If your meter is an analog type, be careful on the lower voltage ranges that you do not "peg" the voltmeter needle. The resistance on all ranges is ____________ ohms.

9. If the resistance reading in step 5 is considerably lower than it was in step 7, your voltmeter is not one of the electronic types and you can determine its ohms-per-volt rating.

10. To determine its ohms-per-volt rating, divide the resistance you recorded in step 5 by the full-scale voltage reading. The ohms-per-volt rating of your voltmeter is ____________ ohms-per-volt.

11. To verify this, divide the resistance you recorded in step 7 by the full-scale voltage range you used. The ohms-per-volt rating should be the same.

12. You can determine the resistance or sensitivity of the voltmeter without using a separate ohmmeter. Virtually all voltmeters have one or more ranges between 2 volts and 10 volts. Ranges of 2 volts, 2.5 volts, 3 volts, 5 volts, and 10 volts are common. Switch your voltmeter to the lowest range between 2 volts and 10 volts.

13. While the voltmeter is set to the range you selected in step 12, connect the voltmeter between the POS and GND terminals of the power supply on the Trainer. Switch the Trainer ON and adjust the + voltage control until the voltmeter indicates full scale. For example, if you selected the 5-volt range, the voltage should be set to 5 volts. Be careful not to exceed the full-scale voltage.

14. Leave the + voltage control set to this point. Connect the circuit shown in Figure 6-30.

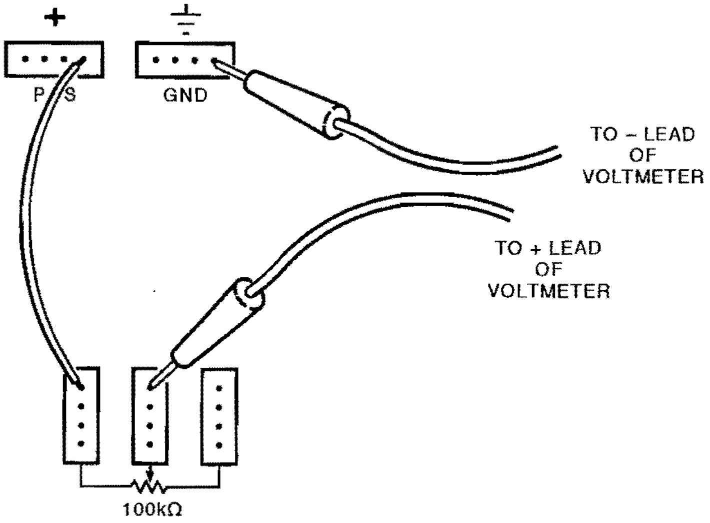

Figure 6-30

Connect the voltmeter in series with the 100kΩ potentiometer.

15. Try to adjust the 100 kilohm potentiometer until the voltmeter indicates exactly half-scale. One of three things will happen:

    a. You are able to adjust the potentiometer so the voltmeter indicates exactly half-scale. If you can, go to step 16.

    b. When you set the potentiometer to its maximum clockwise setting, the voltage drops to less than 9/10-full scale but not to half-scale. In this case, skip to step 20.

    c. You notice only a slight, or no, voltage decrease even when you turn the potentiometer to the maximum clockwise setting. In this case, skip to step 25.

16. Leave the potentiometer set to the point at which the voltmeter indicates half scale. Disconnect the voltmeter and the potentiometer from the power supply.

17. Use the ohmmeter to measure the resistance of the potentiometer between the center wiper and the same outer terminal you used earlier. The resistance is ____________ ohms.

18. Because this resistance dropped one-half of the applied voltage and the voltmeter dropped the other half, the resistance of the voltmeter on this range must also be ____________ ohms.

19. Divide this resistance by the full-scale reading of the voltmeter on the scale you selected. This gives the sensitivity, or ohms-per-volt, rating for your meter. The ohms-per-volt rating of your meter is ____________ ohms. Skip steps 20 through 28 and go directly to the Discussion of this experiment.

20. If you cannot reduce the voltage to half-scale in step 15, adjust the potentiometer until the voltmeter reads 9/10-full scale. For example, if the meter is on the 5-volt range, adjust the potentiometer until the meter reads 9/10 of 5 volts or 4.5 volts.

21. At this time, the meter is dropping 9/10 of the applied voltage while the potentiometer is dropping 1/10. Thus, if you know the resistance of the potentiometer, you can compute the resistance of the voltmeter since its resistance must be 9 times higher. Disconnect the potentiometer and the voltmeter from the power supply without disturbing the setting of the potentiometer.

22. Use the ohmmeter to measure the resistance of the potentiometer between the center wiper and the same outer terminal you used earlier. The resistance is ____________ ohms.

23. Since the potentiometer dropped only 1/10 of the applied voltage and the voltmeter dropped 9/10, the resistance of the voltmeter must be nine times that of the potentiometer, or ____________ ohms.

24. Divide this resistance by the full-scale indication of the voltmeter on the scale you have selected. This gives the sensitivity, or ohms-per-volt, rating for your meter. The ohms-per-volt rating of your meter is ____________ ohms. Skip steps 25 through 28 and go directly to the Discussion of this experiment.

25. If you noticed little or no deflection in step 15, you have an electronic voltmeter (either solid-state or vacuum-tube voltmeter). The input resistance is probably the same on all DC voltage ranges and it is probably 10 megohms or higher. However, you can still estimate the input resistance. Leave the power supply voltage set to the full-scale reading which you set in step 13. Connect the circuit shown in Figure 6-31.

26. The voltmeter now indicates ____________ volts. This reading gives you an indication of the voltmeter's resistance. If the meter indicates less than half scale, its resistance is less than 10 megohms. If it indicates more than half scale, its resistance is greater than 10 megohms.

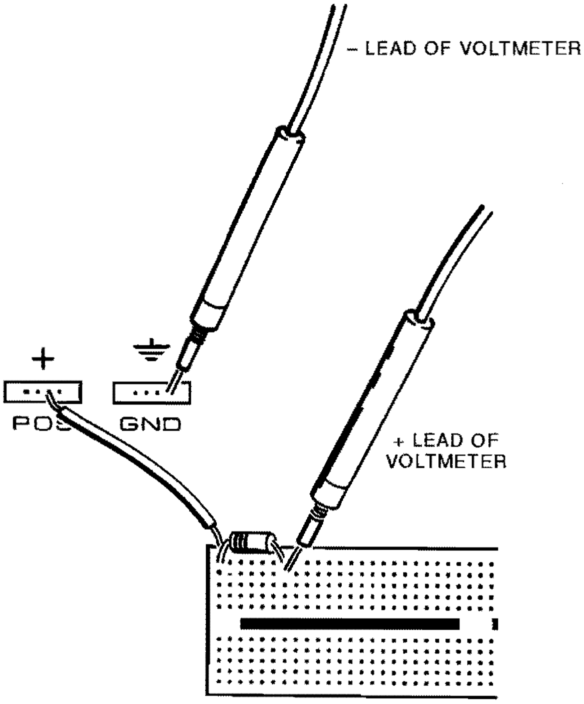

Figure 6-31

Connect the voltmeter in series with the 10 MΩ resistor.

27. You can use Ohm's Law to more accurately approximate the resistance of the meter. First, subtract the meter voltage drop from the applied voltage to determine the voltage drop across the 10 MΩ resistor. The voltage drop is ____________ volts. Next, use Ohm's Law to determine the current through the 10 MΩ resistor. The current in the circuit is ____________ microamperes (μA). Finally, divide the current into the voltmeter reading you obtained in step 26 to determine the resistance of the voltmeter. The resistance of the voltmeter is approximately ____________ ohms

28. Switch the Trainer OFF.

Discussion

In steps 1 through 11, you measured the resistance of the voltmeter directly with a separate ohmmeter. In step 10, you computed the sensitivity of the voltmeter from the values you measured. You did this by dividing the voltmeter's resistance by the full-scale reading for the selected range. For example, if the voltmeter was on the 10-volt range and the resistance you measured was 200,000 ohms, the sensitivity is:

$$\frac{200{,}000\ \Omega}{10\ \text{V}} = 20{,}000 \text{ ohms-per-volt}$$

In the remaining portion of the experiment, you determined the sensitivity or resistance of your meter in another way without using a separate ohmmeter. While the meter was set to a low-voltage range, you connected the voltmeter in series with a 100 kilohm potentiometer across a voltage equal to the full-scale reading of the meter on the range you selected. You then varied the resistance of the potentiometer and observed the result. If you found that you could reduce the voltage across the meter to half scale, you were directed to complete steps 16 through 19. If you could vary the voltage between half scale and 9/10-full scale you were directed to steps 20 through 24. Finally, if you noticed little or no voltage reduction, you were directed to steps 25 through 27.

In steps 16 through 19, you adjusted the potentiometer so that the voltage across the meter was exactly half scale. At this point, the meter resistance must equal to the potentiometer resistance because both drop the same voltage. Consequently, when you measured the resistance of the potentiometer, you also determined the resistance of the meter. You then divided the meter resistance by the full-scale reading to determine the sensitivity.

In steps 20 through 24, you adjusted the potentiometer so that the voltage across the meter was 9/10-full scale. Here, only 1/10 of the voltage was dropped across the potentiometer. Thus, the resistance of the meter was nine times that of the potentiometer. Consequently, you measured the resistance of the potentiometer and multiplied it by nine to find the resistance of the meter. You then divided the full-scale reading into the resistance to find the sensitivity.

Steps 25 through 27 dealt with meters which have a sensitivity greater than 100,000 ohms-per-volt. These are electronic meters which normally have resistances of 10 megohms or more. With most electronic meters, you can approximate the resistance with the method you used here. The meter is connected in series with a 10 megohm resistor across a voltage which is equal to the full-scale reading of the meter. Note the meter reading. Assume that on the 10-volt scale the meter indicates 5.2 volts. This leaves 4.8 volts across the 10 megohm resistor. Consequently, the current through the resistor must be:

$$I = \frac{E}{R} = \frac{4.8\text{ V}}{10{,}000{,}000\ \Omega} = 0.000000\,48\text{ A or }0.48\ \mu\text{A}$$

This same current flows through the meter and causes a 5.2-volt drop. Thus, the resistance of the meter must be:

$$R = \frac{E}{I} = \frac{5.2\text{ V}}{0.48\ \mu\text{A}} = \frac{5.2\text{ V}}{.00000048} = 10.8\text{ M}\Omega\text{ or about }11\text{ M}\Omega$$

EXPERIMENT 16

Loading Effects of the Voltmeter

OBJECTIVE: *To demonstrate that inaccurate voltage measurements can result from voltmeter loading.*

Introduction

In the previous experiment, you determined the sensitivity or input resistance of your voltmeter. You also determined whether you have an electronic meter or an electrical meter. The sensitivity of your meter is important because it determines the loading effect of your meter. If you are familiar with the loading characteristics of your meter, you can recognize situations which will cause inaccurate readings due to loading.

Material Required

1 — Heathkit Analog Trainer
1 — Multimeter with test leads
1 — 100 Ω, 1%, 1/2-watt resistor
1 — 220 kΩ, 5%, 1/2-watt resistor (red-red-yellow-gold)
1 — 1 MΩ, 5%, 1/2-watt resistor (brown-black-green-gold)
1 — 10 MΩ, 5%, 1/2-watt resistor (brown-black-blue-gold)
1 — 200 Ω potentiometer (linear control) #10-917
#22 copper wire

Procedure

1. Use your ohmmeter to measure the resistance of the 100 ohm, 1%, 1/2-watt resistor. The resistor measures ____________ Ω.

2. Connect the ohmmeter from either outer terminal to the center terminal of the 200 Ω potentiometer.

3. Adjust the 200 Ω potentiometer until the ohmmeter indicates the exact resistance you measured in Step 1. The 200 Ω potentiometer is now set to the same value as the 100 Ω resistor.

4. Without disturbing the potentiometer setting, construct the circuit shown in Figure 6-32A.

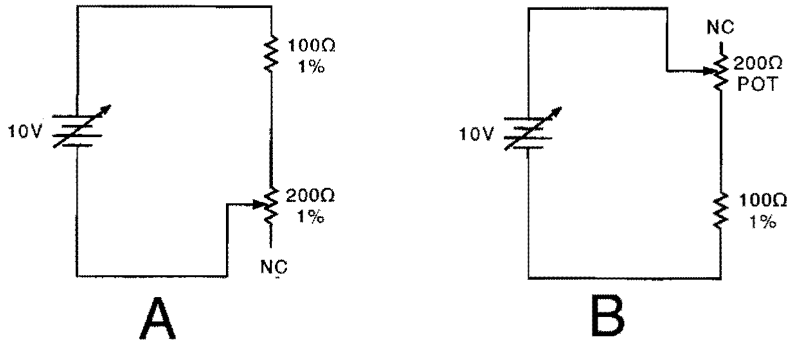

Figure 6-32

Circuits to check voltmeter loading effects.

5. Switch the Trainer ON and connect your voltmeter between the POS and GND terminals. Then adjust the + voltage control for a indication of exactly 10 volts.

6. Measure the voltage drop across the potentiometer. The voltage drop is ____________ volts.

7. Reconfigure the circuit so that it is like the one shown in Figure 6-32B. To do this, simply interchange the leads from the power supply. Now, measure the voltage drop across the 100 ohm resistor. The voltage is ____________ volts.

8. Add the voltage you measured in Step 6 to the voltage you measured in Step 7. Do the two voltages add up to the value you set in Step 5? Are there any signs of voltmeter loading in this example? ____________ .

Discussion

There should be no signs of voltmeter loading because even a very insensitive meter has a high resistance compared to the 100 Ω value of the resistors. Any inaccuracies you encountered are due to difficulties reading the meter and meter accuracy.

The loading effect becomes apparent only when the resistance of the meter approaches that of the resistance across which you are measuring. To demonstrate this, you must use high value resistors to set up a voltage divider.

Procedure (Continued)

9. Construct the circuit shown in Figure 6-33A.

10. Connect your voltmeter between the POS and GND terminals of the power supply on the Trainer. Set the + voltage control so that the voltmeter indicates 6.1 volts.

11. Use Ohm's Law to compute the current flow in the circuit. The current is ____________ μA.

12. Use Ohm's Law to compute the voltage drop across the 1 MΩ resistor (R_1). E_{R1} = __________ V.

13. Use Ohm's Law to compute the voltage drop across the 220 kΩ resistor (R_2). E_{R2} = __________ V.

14. Add E_{R1} to E_{R2}. Does the total equal the source voltage of 6.1 V? ________ .

15. Use your voltmeter to measure the voltage drop across R_1. E_{R1} = ________ V.

16. Reconfigure your circuit like the one shown in Figure 6-33B. Measure the voltage drop across R_2. E_{R2} = __________ volts.

17. Add the value of E_{R1} you recorded in Step 15 to the value of E_{R2} you recorded in Step 16. Does the total equal the source voltage of 6.1 V? __________ . If it doesn't, how do you account for the inaccuracy? ____________________
____
____ .

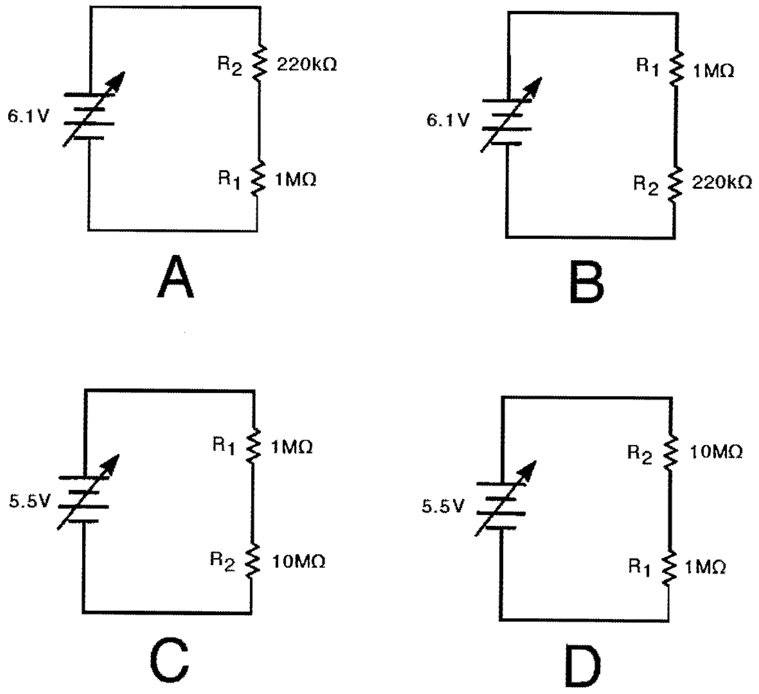

Figure 6-33
Demonstrating voltmeter loading.

Discussion

The current value you computed in Step 11 is:

$$I = \frac{E}{R} = \frac{6.1\ \text{V}}{1.22\ \text{M}\Omega} = 5\ \mu\text{A}$$

The voltage drop across R_1 is:

$$E_{R1} = 5\ \mu\text{A} \times 1\ \text{M}\Omega = 5\ \text{V}$$

The voltage drop across R_2 is:

$$E_{R2} = 5\ \mu\text{A} \times 220\ \text{k}\Omega = 1.1\ \text{V}$$

Notice that $E_{R1} + E_{R2} = 5\ \text{V} + 1.1\ \text{V} = 6.1$ volt.

Thus, the sum of the voltage drops is equal to the voltage rise as you would expect.

When you measure E_{R1} and E_{R2}, you may or may not encounter a great discrepancy in your measurements. If your meter is an *electrical* type, both the E_{R1} and the E_{R2} measurements are lower than you expected. Furthermore, when you add the two voltage drops, the total does not equal the applied voltage. Because the sum of the voltage drops must always equal the applied voltage, the measurements *must* be inaccurate. The inaccuracy of the measurements is caused by the loading effect of the voltmeter as you learned earlier. If your meter has a sensitivity of 20,000 ohms-per-volt and the meter was set to the 10-volt range, it has a resistance of 200 kilohms. Thus, the first voltage measurement was with a 200 kilohm resistance in parallel with R_1. This upsets the operation of the circuit enough to cause very inaccurate readings.

If you have an *electronic* type meter, the resistance on all ranges is probably 10 megohms or greater. The input resistance is still quite large compared to the values of R_1 or R_2. Consequently, you may have noticed little or no loading effect. This illustrates the prime advantage of the electronic meter over the electrical type. If you have an electronic meter continue with Step 18.

Procedure (Continued)

18. In order to demonstrate the loading effect of an electronic meter, you must use higher values of resistors. Replace the 220 kilohm resistor with a 10 megohm resistor so that your circuit is like the one shown in Figure 6-33C.

19. Set the applied voltage to 5.5 V.

20. Compute the current in the circuit. I = ___________ µA.

21. Compute the voltage drop across R_1. E_{R1} = ___________ V.

22. Compute the voltage drop across R_2. E_{R2} = ___________ V.

23. Add E_{R1} to E_{R2}. Does the total equal the applied voltage of 5.5V? _________

24. Measure the voltage drop across R_2. E_{R2} = ___________ V. How does this compare with the value you computed? ___________________________.

25. Next, reconfigure the circuit so that it appears like the one shown in Figure 6-33D. Measure the voltage drop across R_1. E_{R1} = ___________ volts.

26. Add the measured values of E_{R1} and E_{R2}. Does the total equal the applied voltage of 5.5 V? __________.

27. Switch the Trainer OFF.

Discussion

In this case, the resistance values of R_1 and R_2 are so large that even the electronic meter shows a noticeable loading effect. Consequently, the measured values of E_{R1} and E_{R2} are lower than the computed values. Also, the sum of the measured values does not exactly equal the applied voltage.

SUMMARY

The most popular type of meter is the d'Arsonval. It has a permanent magnet and a moving-coil. When current flows through the coil, it develops a magnetic field which interacts with the permanent magnet's field. The coil rotates as is described by the right-hand motor rule. The amount of rotation is proportional to the current.

The main parts of the d'Arsonval meter movement are the moving-coil, the permanent magnet, the scale, pivots, bearings, springs, retaining pins, counter weights, and a zero adjust mechanism.

A variation of the d'Arsonval movement is the taut-band movement. In this device, thin metal bands replace the pivots, jeweled bearings, and spiral springs. This makes a more sensitive and more rugged movement.

You can use a sensitive meter movement to construct a multirange ammeter. A 50 μA movement can be used to measure a much higher current value by connecting a small value resistor (called a shunt) in parallel with the movement.

To determine the proper value of shunt, you must know the resistance of the meter movement. If the resistance of the meter movement is 1000 ohms, you can double the current range by connecting a 1000 ohm resistor in parallel. In the same way, if the shunt is to carry 9 times as much current as the meter movement, the shunt resistance must be one-ninth that of the meter movement.

The accuracy of a meter movement is specified as a percentage of error at full-scale deflection. If a 100 mA meter has an accuracy of ± 3%, the reading may be off by as much as ± 3 mA at any point on the scale.

You can use a current-operated meter movement to measure voltage. A 1 mA, 1000 Ω meter movement indicates full scale when the applied voltage is:

$$E = I \times R = 1\,\text{mA} \times 1\,\text{k}\Omega = 1\,\text{V}.$$

To extend the voltage range, you connect a voltage dropping resistor (called a multiplier) in series with the meter movement. To extend the range of the above meter to 10 V, the multiplier must drop 9 V when the current is 1 mA. Thus, its value must be:

$$R = \frac{E}{I} = \frac{9\,\text{V}}{1\,\text{mA}} = 9\,\text{k}\Omega$$

The sensitivity of a meter movement is specified in ohms-per-volt. To determine it, you divide the full-scale current rating into 1 V. Thus, a 1 mA meter has a sensitivity of:

$$\frac{1\ \text{V}}{1\ \text{mA}} = 1000 \text{ ohms-per-volt}$$

The ohms-per-volt rating is important because it indicates the loading effect of a voltmeter. The higher the sensitivity, the less the loading effect.

The series ohmmeter consists of a battery, a meter movement, and a resistance that are all connected in series. Zero ohms is indicated by a full-scale deflection while infinite ohms are indicated by no deflection. The internal series resistance of the ohmmeter circuit must allow a full-scale current to flow when the test leads are shorted together. Thus, a 50 µA meter movement and a 4.5-volt battery require an internal resistance of:

$$R = \frac{E}{I} = \frac{4.5\ \text{V}}{50\ \mu\text{A}} = 90\ \text{k}\Omega$$

A multimeter is a combination voltmeter, ohmmeter, and ammeter in a single case, and uses a single meter movement. To measure voltage, multiplying resistors are switched in series. To measure current, shunt resistors are switched in parallel. To measure ohms, a battery and zero ohms adjust are switched in series with the meter movement.

UNIT EXAMINATION

1. The d'Arsonval meter movement is characterized by a:

   A. moving-coil which rotates in the field of a permanent magnet.
   B. permanent magnet which rotates in the field of an electromagnet.
   C. moving-coil which rotates in the field of an electromagnet.
   D. permanent magnet which rotates in the field of a second permanent magnet.

2. A variation of the d'Arsonval meter movement uses thin metal bands to replace the pivots, jeweled bearings, and spiral springs of the conventional movement. This type of movement is called the:

   A. current-operated meter movement.
   B. moving-coil meter movement.
   C. permanent-magnet meter movement.
   D. taut-band meter movement.

3. You can increase the range of an ammeter by:

   A. switching a higher rated meter movement into the ammeter circuit.
   B. placing a dropping resistor in series with the meter movement.
   C. placing a resistor in parallel with the meter movement.
   D. using a higher voltage battery in the ammeter circuit.

4. You can increase the range of a voltmeter by:

   A. placing a higher value dropping resistor in series with the meter movement.
   B. placing a lower value dropping resistor in parallel with the meter movement.
   C. using a higher value shunt resistor.
   D. placing a lower value dropping resistor in series with the meter movement.

5. The accuracy of a meter is specified as a percentage of error at:

   A. a full-scale deflection.
   B. a mid-scale deflection.
   C. 50 μ amps.
   D. 1 volt.

6. To minimize the loading effect of a voltmeter:

   A. the resistance of the voltmeter should be as low as possible.
   B. the resistance of the voltmeter should be as high as possible.
   C. the sensitivity of the voltmeter should be 1000 ohms per volt.
   D. connect the voltmeter in series rather than in parallel.

7. A 9-volt battery is used in conjunction with a 1 mA meter movement and a series resistance to form a series ohmmeter. What is the half-scale reading of this ohmmeter?

   A. 18,000 ohms.
   B. 4,500 ohms.
   C. 450 ohms.
   D. 9,000 ohms.

8. The basic series ohmmeter circuit can be modified to measure lower values of resistance. This is done by:

   A. using a higher value battery voltage.
   B. placing a low value resistor in parallel with the meter movement and its series resistance.
   C. placing a low value resistor in parallel with the battery.
   D. placing a high value resistor in series with the meter movement and battery.

9. Refer to the multimeter shown in Figure 6-25. What is the sensitivity of the meter movement that is used in this instrument?

   A. 2000 ohms-per-volt.
   B. 1000 ohms-per-volt.
   C. 20,000 ohms-per-volt.
   D. 40,000 ohms-per-volt.

10. Refer again to Figure 6-25. What is the proper value of R_6?

   A. 2 MΩ.
   B. 10 MΩ.
   C. 1 MΩ.
   D. 200 kΩ.

11. Refer again to Figure 6-25. If the HIΩ range is ten times higher than the LOΩ range, what voltage should B_2 be?

    A. 9 V.
    B. 15 V.
    C. 1.5 V.
    D. 4.5 V.

12. Refer again to Figure 6-25. What is the proper value of R_1?

    A. 1000 ohms.
    B. 5 ohms.
    C. 0.1 ohm.
    D. 1 ohm.

13. The most accurate meter readings are possible when you make the reading:

    A. at the low end of the scale.
    B. in the middle of the scale.
    C. at the high end of the scale.
    D. at any point on the scale.

14. The meter reading error that occurs when you observe the meter from the right or left rather than from straight on is called:

    A. index error.
    B. slant-view error.
    C. parallax error.
    D. registration error.

15. The ZERO OHMS adjustment in an ohmmeter is used to:

    A. change the scale from linear to non-linear.
    B. determine the range of the meter.
    C. compensate for the deterioration of the battery within the ohmmeter.
    D. accomplish the change between a shunt and a series ohmmeter.

16. An ammeter can introduce an error when you use it to measure current because:

    A. the meter itself induces some small amount of current into the circuit.
    B. the meter has a small amount of internal resistance that changes the characteristics of the circuit.
    C. each multiplier resistor within the meter contributes to the overall resistance of the circuit.
    D. the battery in the ammeter gradually deteriorates.

17. The component that increases the range of the voltmeter is the:

    A. multiplier resistor.
    B. shunt resistor.
    C. shunt winding.
    D. d'Arsonval movement.

18. The component that increases the range of the ammeter is the:

    A. multiplier resistor.
    B. shunt resistor.
    C. shunt winding.
    D. taut band.

EXAMINATION ANSWERS

1. A — The d'Arsonval meter movement is characterized by a moving-coil which rotates in the field of a permanent magnet.

2. D — The taut-band meter movement is named for the metal bands which replace the pivots, jeweled bearings, and spiral springs of the conventional d'Arsonval movement.

3. C — You can increase the range of an ammeter by placing a lower value resistor in parallel with the meter movement. The resistor is called a shunt and its purpose is to detour a large portion of the current around the meter movement.

4. A — You can increase the range of a voltmeter by placing a higher value dropping resistor in series with the meter movement. The resistor is called a multiplier and its purpose is to limit the current through the meter movement to a safe value.

5. A — The accuracy of a meter is specified as a percentage of error at full-scale deflection.

6. B — To minimize the loading effect of a voltmeter the resistance of the voltmeter should be as high as possible. Since the voltmeter is always connected in parallel with a circuit, it has less effect when its resistance is high. Ideally, the voltmeter would have infinite resistance.

7. D — The half-scale reading is 9000 ohms. You must first find the internal series resistance of the ohmmeter with the test leads shorted together. This is the 0 ohms condition. In this condition, the 9-volt battery must produce 1 mA of current to cause full-scale deflection. Thus, the internal resistance is:

$$R = \frac{E}{I} = \frac{9\text{ V}}{1\text{ mA}} = 9000\text{ ohms.}$$

This resistance is always in series with the ohmmeter circuit. Now to cause half-scale deflection or 0.5 mA, the total resistance must be:

$$R = \frac{E}{I} = \frac{9\text{ V}}{0.5\text{ mA}} = 18{,}000\text{ ohms.}$$

However, 9000 ohms are provided by the internal resistance. Thus, the unknown resistance which causes half-scale deflection is 9000 ohms. Consequently, the half-scale reading of the ohmmeter is 9000 ohms.

8. B — You can modify the series ohmmeter to measure lower values of resistance by placing a low value resistor in parallel with the meter movement and the series resistance.

9. C — The sensitivity is 20,000 ohms-per-volt. To find the sensitivity, divide the full-scale current rating into 1 volt.

$$\text{Sensitivity} = \frac{1\ \text{V}}{50\ \mu\text{A}} = 20{,}000 \text{ ohms per volt.}$$

10. A — The proper value for R_6 is 2 MΩ. It must limit the current to 50 μA when the applied voltage is 100 V. Since the resistance of the meter is negligible by comparison, you can ignore it.

$$R_6 = \frac{100\ \text{V}}{50\ \mu\text{A}} = 2\ \text{M}\Omega.$$

11. B — The B_2 voltage should be 15 volts. Since the range is increased by a factor of 10, both the battery voltage and the series resistance must be increased by a factor of 10.

12. D — R_1 should be 1 ohm. On the 100 mA range, R_1 must conduct all of the current except 50 μA. That is, it must conduct approximately 2000 times as much current as the meter movement. Thus, the value of R_1 must be about 1/2000 that of the movement or about 1 ohm.

13. C — The most accurate meter readings are possible when you make the reading at the high end of the scale. The accuracy of a reading gets progressively worse as you approach the low end of the scale.

14. C — If you look at a meter from any angle other than straight on, a reading error known as parallax error occurs.

15. C — The ZERO OHMS adjustment is used to compensate for the normal deterioration of the battery within the ohmmeter.

16. B — An ammeter has a small amount of internal resistance. No matter how small this resistance is, when the ammeter is connected to a circuit its internal resistance limits the current through the circuit. If the resistance of the circuit is small enough, the amount of error introduced by the internal resistance of the meter can be quite substantial.

17. A — A multiplier resistor increases the range of a voltmeter. This resistor is connected in series with the meter movement.

18. B — A shunt resistor increases the range of an ammeter. This resistor is connected in parallel with the meter movement.

UNIT 7

DC CIRCUITS

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INTRODUCTION

The purpose of this unit is to expand your knowledge of basic DC circuits. After a brief review of series and parallel circuits, you are introduced to some new applications of these circuits. Next you will study an entirely new circuit called a bridge. Finally, you will learn several new analytical tools for evaluating circuits.

UNIT OBJECTIVES

When you complete this unit, you will be able to:

1. Define the following terms: Bleeder current, series dropping resistor, voltage divider, bridge network, linear circuit, and bilateral circuit.

2. Given the current and voltage requirements for the separate loads, calculate the values of the resistors in a voltage divider.

3. Given the values of the resistors in a bridge network, determine whether or not the bridge is balanced.

4. Name three applications for a bridge circuit.

5. Use the superposition theorem to analyze a simple network.

6. Use the Thevenin's theorem to analyze a simple network.

7. Use Norton's theorem to analyze a simple network.

8. Use Kirchhoff's law to calculate unknown currents and voltages in a simple network.

9. Convert a Thevenin equivalent circuit to a Norton equivalent circuit.

UNIT ACTIVITY GUIDE

	Completion Time
☐ Read "Simple Circuits."	__________
☐ Complete Programmed Review Frames 1 — 10.	__________
☐ Read "Voltage Dividers. "	__________
☐ Complete Programmed Review Frames 11 — 23.	__________
☐ Read "Bridge Circuits."	__________
☐ Complete Programmed Review Frames 24 — 29.	__________
☐ Complete Experiment 17.	__________
☐ Read "Kirchhoff's Law. "	__________
☐ Complete Programmed Review Frames 30 — 46.	__________
☐ Read "Superposition Theorem."	__________
☐ Complete Programmed Review Frames 47 — 57.	__________
☐ Read "Thevenin's Theorem."	__________
☐ Complete Programmed Review Frames 58 — 68.	__________
☐ Read "Norton's Theorem."	__________
☐ Complete Programmed Review Frames 69 — 83.	__________
☐ Complete Experiment 18.	__________
☐ Study Summary.	__________
☐ Complete Unit Examination.	__________
☐ Check Examination Answers.	__________

SIMPLE CIRCUITS

Throughout your study of electronics, you will see certain circuits repeated over and over again. Some of the most used circuits are the easiest to understand. You already studied the characteristics of several types of simple circuits. These included the series circuit, the parallel circuit, and the series-parallel circuit. In this unit, you will first review the characteristics of these circuits. Then you will go on to some more advanced concepts.

Series Circuit

In a series circuit, current flows through all of the components in the circuit shown in Figure 7-1. In such a circuit, you may wish to find the current, the voltage dropped by any resistor, or the power dissipated by any resistor.

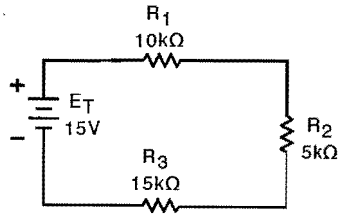


Figure 7-1
The series circuit.

The current is the same in all of the resistors. You determine it by dividing the total resistance into the applied voltage. The total resistance (R_T) in a series circuit is equal to the sum of the individual resistances. Thus, in Figure 7-1:

$$R_T = R_1 + R_2 + R_3$$

$$R_T = 10\ \text{k}\Omega + 5\ \text{k}\Omega + 15\ \text{k}\Omega$$

$$R_T = 30\ \text{k}\Omega$$

Once you know the total resistance, you can determine the current:

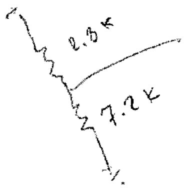
$$I = \frac{E}{R_T}$$

$$I = \frac{15\ \text{V}}{30\ \text{k}\Omega}$$

$$I = \frac{15\ \text{V}}{30{,}000\ \Omega}$$

$$I = 0.0005\ \text{A} = 0.5\ \text{mA}$$

2.8
720 K
16K



Since the current is the same in all of the resistors, you can determine the voltage drop across any one resistor by multiplying the current times the value of that resistor. For example, the voltage across R_1 is:

$$E_{R1} = I \times R_1$$

$$E_{R1} = 0.0005\ \text{A} \times 10{,}000\ \Omega$$

$$E_{R1} = 5\ \text{volts}$$

In the same way E_{R2} is:

$$E_{R2} = I \times R_2$$

$$E_{R2} = 0.0005\ \text{A} \times 5000\ \Omega$$

$$E_{R2} = 2.5\ \text{volts}$$

Also, E_{R3} is:

$$E_{R3} = I \times R3$$

$$E_{R3} = 0.0005\ \text{A} \times 15{,}000\ \Omega$$

$$E_{R3} = 7.5\ \text{volts}$$

The voltage drops across the three resistors are next worked out to illustrate another important characteristic of the series circuit. The applied voltage, E_T, is equal to the sum of the voltage drops. That is:

$$E_T = E_{R1} + E_{R2} + E_{R3}$$

$$E_T = 5\ \text{V} + 2.5\ \text{V} + 7.5\ \text{V}$$

$$E_T = 15\ \text{V}$$

Finally, the power dissipated by any resistor is equal to the current times the voltage drop across the resistor. Thus, the power dissipated by R_1 is:

$$P_{R1} = I \times E_{R1}$$

$$P_{R1} = 0.0005\ \text{A} \times 5\ \text{volts}$$

$$P_{R1} = 0.0025\ \text{W or } 2.5\ \text{mW}$$

Review the above equations until you can compute any of the electrical quantities in the circuit.

Parallel Circuit

A simple parallel circuit is shown in Figure 7-2. In a parallel circuit, the same voltage is applied to each branch. Thus, in Figure 7-2 the voltage is the same across each resistor:

$$E_T = E_{R1} = E_{R2} = E_{R3} = 15 \text{ volts}$$

That is, 15 volts is dropped across each resistor.

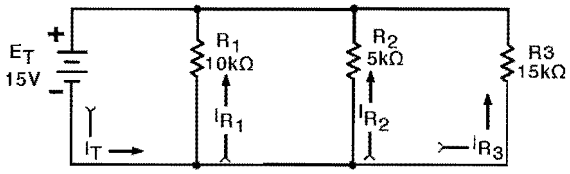


Figure 7-2
The parallel circuit.

To find the current through any resistor, you divide the voltage by the resistance value of that resistor. For example, the current through R_1 is:

$$I_{R1} = \frac{E}{R_1}$$

$$I_{R1} = \frac{15 \text{ V}}{10 \text{ k}\Omega}$$

$$I_{R1} = \frac{15 \text{ V}}{10{,}000\ \Omega}$$

$$I_{R1} = 0.0015 \text{ A} = 1.5 \text{ mA}$$

Also, I_{R2} is:

$$I_{R2} = \frac{E}{R_2} = \frac{15 \text{ V}}{5{,}000\ \Omega} = 3 \text{ mA}$$

And I_{R3} is:

$$I_{R3} = \frac{E}{R_3} = \frac{15 \text{ V}}{15{,}000\ \Omega} = 1 \text{ mA}$$

Now, since the total current is the sum of the branch currents:

$$I_T = I_{R1} + I_{R2} + I_{R3}$$

$$I_T = 1.5\text{ mA} + 3\text{ mA} + 1\text{ mA} = 5.5\text{ mA}$$

You can determine the total current in another way by dividing the total resistance (R_T) into the applied voltage. To find the total resistance, you must use the equation for parallel circuits:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

$$R_T = \frac{1}{\frac{1}{10{,}000\ \Omega} + \frac{1}{5{,}000\ \Omega} + \frac{1}{15{,}000\ \Omega}}$$

$$R_T = \frac{1}{.0001 + .0002 + .00006667}$$

$$R_T = \frac{1}{.00036667}$$

$$R_T = 2727\text{ ohms.}$$

Now use this value of R_T, to find the total current:

$$I_T = \frac{E}{R_T} = \frac{15\text{ V}}{2727\ \Omega} = 0.0055\text{ A} = 5.5\text{ mA}$$

Note that this agrees with the value you computed when you added the individual branch currents.

You can find the power dissipated in any resistor by multiplying the current through the resistor by the voltage dropped by the resistor. For example, the power dissipated by R_1 is:

$$P_{R1} = I_{R1} \times E_{R1} = 0.0015\text{ A} \times 15\text{ V} = 0.0225\text{ W} = 22.5\text{ mW}$$

Series-Parallel Circuit

Often a circuit will have both series and parallel current paths as shown in Figure 7-3A. To compute electrical quantities in this type of circuit, you must first simply the circuit by redrawing it as shown in Figure 7-3B.

Notice that the two parallel resistors (R_2 and R_3) have been replaced with an equivalent resistance (R_A). You can use the following equation to determine the value of R_A:

$$R_A = \frac{R_2 \times R_3}{R_2 + R_3}$$

$$R_A = \frac{2{,}000 \times 2{,}000}{2{,}000 + 2{,}000}$$

$$R_A = \frac{4{,}000{,}000}{4{,}000}$$

$$R_A = 1000\,\Omega = 1\,\text{k}\Omega$$

The resulting circuit shown in Figure 7-3B is just like any other series circuit.

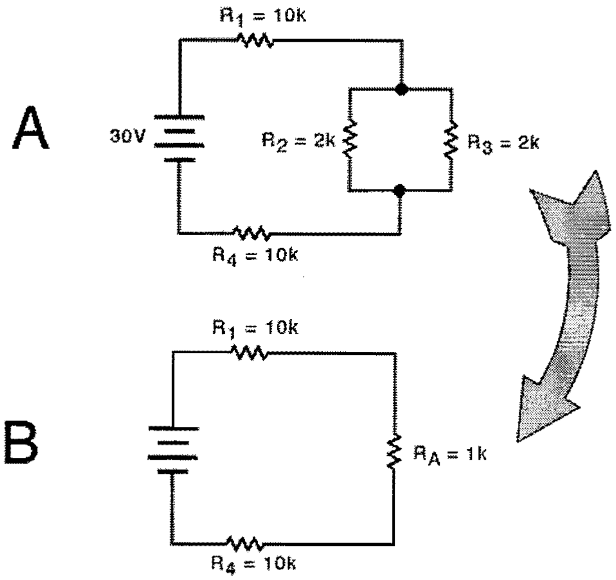


Figure 7-3

The series-parallel circuit.

Programmed Review

1. In a series circuit, the __________ is the same at all points in the circuit.

2. (current) In the series circuit shown in Figure 7-4A, the total resistance is __________ .

3. (10 kΩ) The current in the circuit is __________ .

4. (1 mA) The voltage drop across R_1 is __________ .

5. (1 Volt) The power dissipated by R_5 is __________ .

6. (4 mW) In a parallel circuit, the __________ is the same across all branches.

7. (voltage) In the parallel circuit shown in Figure 74B, the current through R_1 is __________ .

8. (2 mA) The total current (I_T) is __________ .

9. (12 mA) The power dissipated by R_3 is __________ .

10. (72 mW)

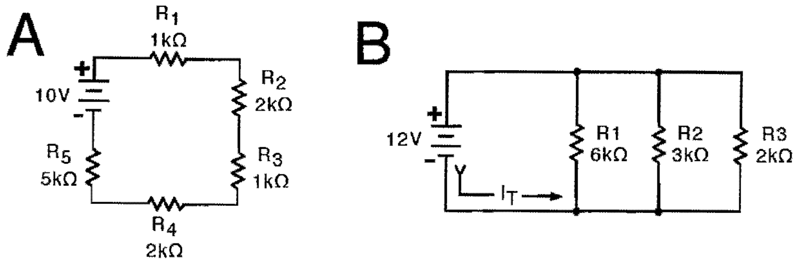

A
R1
1kΩ
R2
2kΩ
10V
+
-
R5
5kΩ
R3
1kΩ
R4
2kΩ
B
12V
+
-
R1
6kΩ
R2
3kΩ
R3
2kΩ
IT

Figure 7-4

Circuits for the review problems.

VOLTAGE DIVIDERS

One of the most useful series-parallel circuits is the voltage divider. It is frequently used at the output of a power supply to provide a number of output voltages which are distributed to different circuits.

The design of a voltage divider is complicated by the current drawn by the load. If you could ignore the load current, the design of the voltage divider would be extremely simple. For example, suppose you have a 30-volt power supply (or battery pack) and that you wish to obtain voltages of +15 volts and +30 volts. Figure 7-5A shows a circuit which appears to perform this function. Since R_1 and R_2 are the same size, each drops one-half of the applied voltage. If you place a voltmeter across R_1, it will read +15 volts. Thus, the top of R_1 is at +15 volts with respect to ground. Naturally, the top of R_2 is at +30 volts with respect to ground. Thus, the circuit appears to meet the requirements set above. However, if you examine the circuit more closely, you find that the above conditions exist only under the *no load* condition.

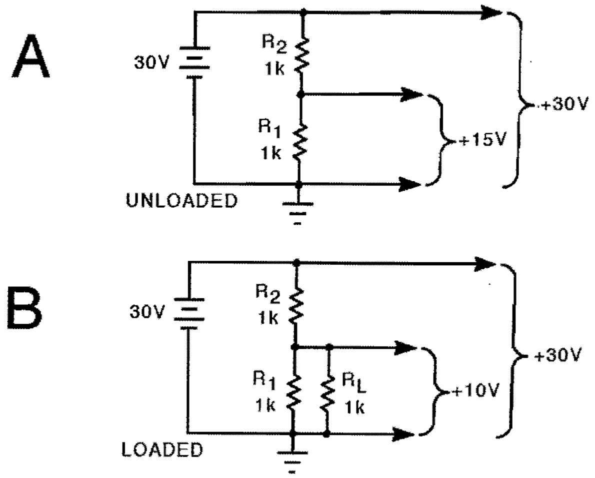


Figure 7-5
Simple voltage divider.

When we attempt to use the +15 volts at the top of R_1 to drive a load, an interesting thing happens as shown in Figure 7-5B. Here a 1 kΩ load (R_L) is connected across the +15 volt supply. Notice that R_L is in parallel with R_1. Thus, the equivalent resistance of R_1 and R_L in parallel is:

$$R_T = \frac{R_1 \times R_L}{R_1 + R_L} = \frac{1000 \times 1000}{1000 + 1000} = \frac{1{,}000{,}000}{2000} = 500\ \Omega$$

The resistance from the top of R_1 to ground drops from 1 kΩ to 500 Ω. R_2 is twice as large as the equivalent resistance. Consequently, R_2 drops 2/3 of the applied voltage while the equivalent resistance of R_1 and R_L drops 1/3. That is, R_2 drops 20 volts while R_1 and R_L in parallel drop only 10 volts. Thus, the voltage from the top of R_1 to ground decreases from +15 V to +10 V. When a load is connected across the divider, the divider no longer fulfills the requirements which were originally specified.

The point is, that in order to design a workable voltage divider, you must consider the current which flows through the load. To illustrate this point, assume you have three loads which must be driven from a single 12-volt power supply. Assume that the first load requires +12 volts at 1 ampere. Also assume that the second load requires 8 volts at 0.6 amperes, while the third load requires 4 volts at 0.2 amperes. Figure 7-6 shows what the final circuit looks like.

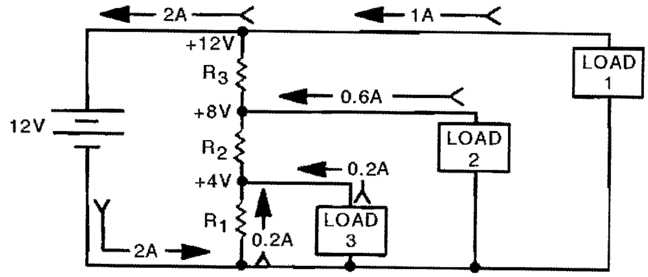


Figure 7-6

Designing the voltage divider.

Three resistors are used to develop the three desired voltages. The values of the three resistors are not given. In order to design the circuit, you must determine the values required for these resistors.

You know that you can use Ohm's Law to determine the value of any resistor, if you know the current through the resistor and the voltage developed across it. If you analyze Figure 7-6 closely, you see that it provides enough information to allow you to find the resistor values.

Look at R_1. The current through R_1 is given as 0.2 ampere. This is the only current in the circuit which is not flowing through one of the loads. This current is called the *bleeder* current, and R_1 is called the bleeder resistor. Because the bleeder current does not flow through any of the loads, its value is not critical. It is generally selected to be about 10 percent of the total circuit current. For example, in Figure 7-6 the total current drawn from the supply is 2 amperes. Therefore, a bleeder current of 0.2 amperes is selected.

Once you determine what the bleeder current is to be, you can determine the value of R_1. The current through R_1 is 0.2 A and the voltage across R_1 is 4 V. Therefore:

$$R_1 = \frac{4\ \text{V}}{0.2\ \text{A}} = 20\ \Omega$$

You can use a similar procedure to determine the required value of R_2. The current through R_2 is the sum of the 0.2 A bleeder current through R_1 and the 0.2 A through load 3. Therefore, the current through R_2 is 0.4 A. The voltage at the bottom of R_2 is + 4 V while that at the top of R_2 is + 8 V. Consequently, the voltage across R_2 is 4 volts. Therefore:

$$R_2 = \frac{4\ \text{V}}{0.4\ \text{A}} = 10\ \Omega$$

Finally, look at R_3. The current through R_3 is the sum of the 0.6 A through load 2 and the 0.4 A through R_2. Thus, the total current through R_3 is 1 A. The bottom end of R_3 is at +8 V while the top of R_3 is at +12 volts. Therefore, the voltage across R_3 is 4 volts. With Ohm's Law, you find that the value of R_3 is:

$$R_3 = \frac{4\ \text{V}}{1\ \text{A}} = 4\ \Omega$$

You can use this procedure to design a voltage divider for one or more loads. All you need to know is the source voltage plus the voltage and current requirements of each load.

To summarize, the step-by-step procedure is as follows:

1. Arbitrarily select a bleeder current which is about 10 percent of the total current in the circuit.

2. Use the bleeder current and the lowest voltage required by a load to compute the value of the bleeder resistor.

3. Use the total current through each resistor and the voltage dropped by the resistor to determine the resistance values that are required.

A special form of voltage divider which is frequently used in electronics consists of a resistor in series with a load of some type. The resistor is called a *series dropping* resistor. Its purpose is to ensure that the load operates at its proper voltage and current rating. For example, consider the problem of using a 5-volt relay in a system in which the only source of power is 12 volts. Assume that the relay is designed to operate at 100 mA. The solution is to connect a resistor in series with the relay coil so that the current is limited to 100 mA. Also, since the relay must operate at 5 volts, the series resistor must drop: 12 – 5 = 7 volts. Thus, the size of the resistor must be:

$$R = \frac{E}{I} = \frac{7\text{ V}}{100\text{ mA}} = 70\text{ ohms.}$$

Dropping resistors are often used in series with relays, light bulbs, etc. The series dropping resistor and its load form a very simple voltage divider.

Programmed Review

11. Figure 7-7 shows a voltage divider which provides voltages for three separate loads. The voltage and current requirements for each load are given. The total current demanded by the three loads is __________ mA.

12. (450 mA) R_1 is the bleeder resistor. Assume you want a bleeder current of 50 mA through R_1. What is the proper resistance value of R_1? ____________ .

13. (100 Ω) The current through R_2 is the sum of the current through R_1 and the current through load 3. Thus, the current through R_2 is ____________ mA.

14. (100 mA) The voltage at the top of R_2 is +10 V, while the voltage at the bottom of R_2 is +5 V. The voltage drop across R_2 is ____________ volts.

15. (5 volts) What is the proper resistance value of R_2? ____________ .

16. (50 Ω) The current through R_3 is the sum of the current through R_2 plus the current through load 2. Thus, the current through R_3 is ____________ mA.

17. (200 mA) The voltage at the top of R_3 is +20 V while the voltage at the bottom of R_3 is +10 V. The voltage drop across R_3 is ____________ volts.

18. (10 volts) What is the proper resistance value of R_3? ____________ .

19. (50 Ω) When you use the computed values of R_1, R_2, and R_3, each load will receive its specified voltage and current.

20. A simple voltage divider is often formed by a series dropping resistor and a load. For example, suppose a relay coil has a resistance of 1 kΩ and is designed to operate with a current of 10 mA. The voltage at which the relay is designed to operate is __________ volts.

21. (10 volts) Assume that this relay is to be used in a system where the only voltage available is 24 volts. Obviously then, the series dropping resistor must drop __________ volts.

22. (14 volts) Since the current through the resistor must be 10 mA, the resistor value required is __________ ohms.

23. (1400 ohms)

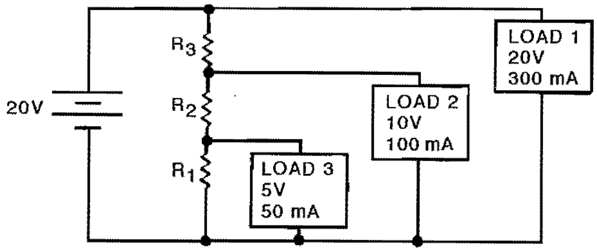


Figure 7-7

Find the values of R_1, R_2, and R_3.

BRIDGE CIRCUITS

Another type of series-parallel circuit which is widely used is the bridge circuit. In its simplest form, the bridge circuit is made up of four resistors connected as shown in Figure 7-8A. The circuit has two input terminals and two output terminals. In DC applications, the input terminals are connected to some source of DC voltage such as a battery. Often a meter is connected across the output terminals as shown in Figure 7-8B.

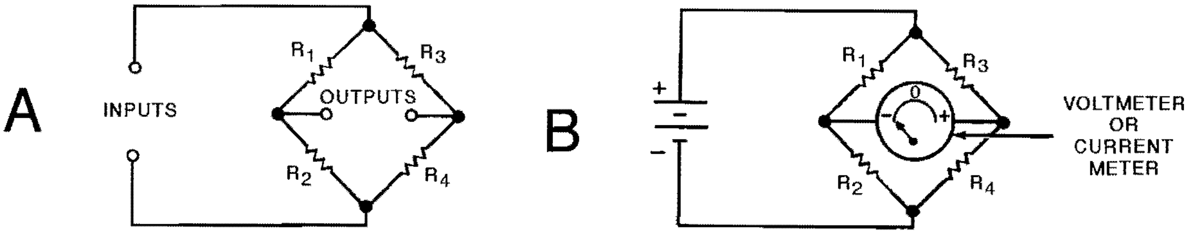


Figure 7-8

The bridge circuit.

Balanced Bridge

Before you look at some of the uses for bridge circuits, you need to first investigate their characteristics. A bridge circuit may be either balanced or unbalanced. In a balanced bridge circuit, the voltage across the two output terminals is 0 volts. If the circuit shown in Figure 7-8B is balanced, a voltmeter or current meter connected across the output terminals (as shown) would indicate zero.

An example of a balanced bridge is shown in Figure 7-9A. Notice that R_1 has the same value as R_2. Thus, the voltage at point A with respect to ground must be one half the applied voltage or +10 volts. The voltage at point B is also +10 volts for the same reason. Therefore, point A is at the same potential as point B. A voltmeter connected from point A to point B will indicate 0 volts. Also, a current meter would read 0 µA because no current flows unless there is a difference in potential. Notice that the bridge is balanced when all four resistors have the same value.

Figure 7-9B shows that a balanced condition can exist even when all of the resistors have different values. Here, you can determine the voltage at point A if you know the current through R_2 (I_A).

$$I_A = \frac{E}{R_1 + R_2} = \frac{30\text{ V}}{1\text{ k}\Omega + 2\text{ k}\Omega} = \frac{30\text{ V}}{3\text{ k}\Omega} = \frac{30\text{ V}}{3000\ \Omega} = 0.01\text{ A}$$

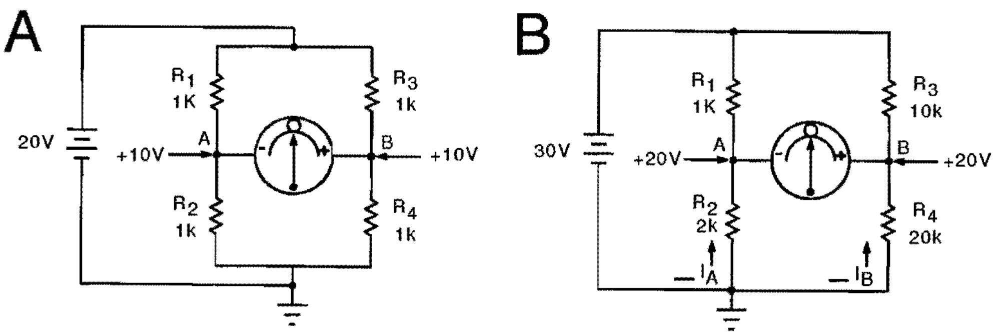


Figure 7-9

The balanced bridge.

Now, you can determine the voltage across R_2:

$$E_{R2} = I_A \times R_2$$

$$E_{R2} = 0.01\text{A} \times 2000\ \Omega$$

$$E_{R2} = 20\text{ V}$$

Thus, the voltage at point A with respect to ground is +20 volts.

You can use a similar procedure to determine the voltage at point B. You will find that it is also +20V. Thus, there is no difference of potential between points A and B. Consequently, the bridge is balanced.

If you examine Figure 7-9B carefully, you will see that R_2 is twice the value of R_1 and that R_4 is twice the value of R_3. R_1 and R_2 form a voltage divider which determines the voltage at point A. R_3 and R_4 form a divider which determines the voltage at point B. As long as R_1 and R_2 are the same ratio as R_3 and R_4, the bridge is balanced. Expressed as an equation, the bridge is balanced when:

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

Notice that this equation is correct for both of the examples shown in Figure 7-9.

Unbalanced Bridge

Figure 7-10A shows a variation of the basic bridge circuit. Here, R_4 has been replaced with a potentiometer. If you set R_4 to the same value as the other three resistors (200 Ω), the bridge is balanced. Both point A and point B are at +15 volts with respect to ground.

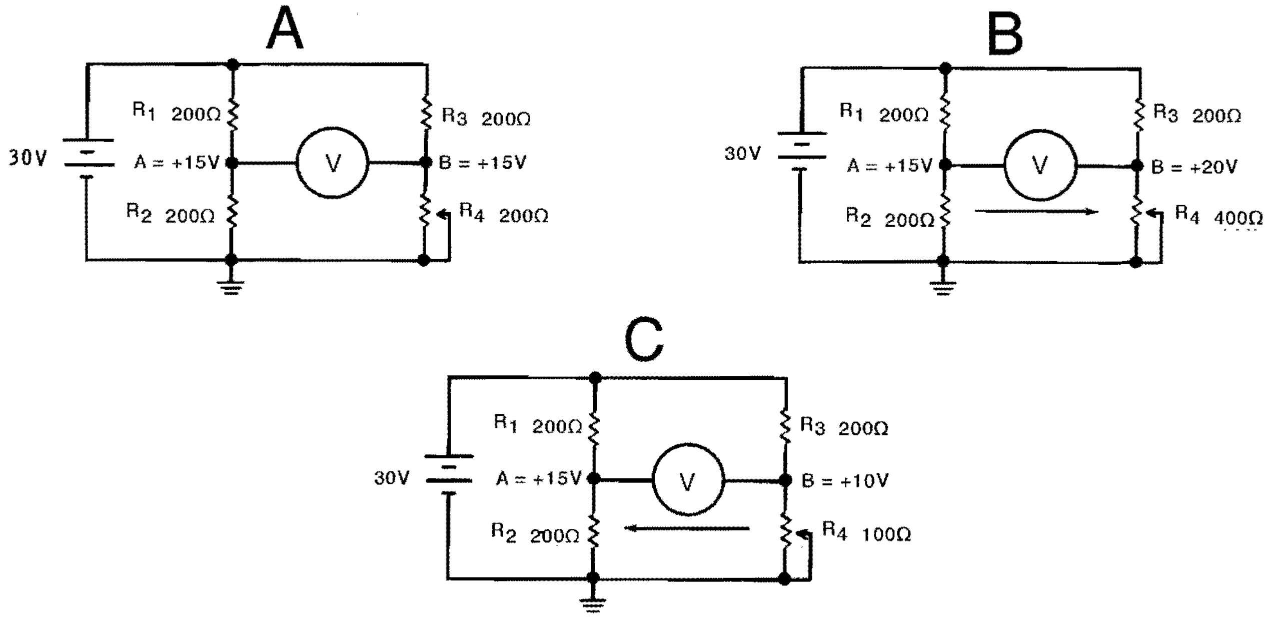


Figure 7-10
Unbalancing the bridge.

By moving the arm of R_4, you can upset the balanced condition. For example, in Figure 7-10B, R_4 is reset to 400 Ω. The voltage at point A remains at +15 volts since neither R_1 nor R_2 are changed. However, the voltage at point B changes. Because R_4 is now twice as large as R_3, it drops twice as much voltage as R_3. Thus, R_4 now drops 20 V while R_3 drops only 10 V. Consequently, the voltage at point B is +20 V with respect to ground. The bridge is no longer balanced because a difference of potential exists between points A and B. Because point B is more positive than point A, a minute current flows through the voltmeter as shown. A voltmeter connected in this way would read the 5 volt difference of potential.

Figure 7-10C shows that you can also upset the bridge in the opposite direction by making the value of R_4 smaller than the value of R_3. Here, R_4 develops only 10 volts. Hence, the voltage at point B is only +10 volts. Thus current flows in the opposite direction through the meter.

Wheatstone Bridge

Now that you have an understanding of how the bridge circuit operates, you will see how it can be put to practical use. The first useful application of the bridge circuit is the *wheatstone bridge.* The wheatstone bridge is a device that measures resistance.

A simple wheatstone bridge is shown in Figure 7-11. R_1 and R_2 are fixed resistors that are carefully matched so that they are the same value. R_S is a 1 kΩ potentiometer which has a calibrated dial. At any setting, you can read its value directly from the dial. R_X is the unknown resistance which you wish to measure. It is connected between the two test leads of the bridge. The voltmeter has been replaced with a very sensitive current meter called a galvanometer. Unlike the current meters discussed earlier, the galvanometer can measure current flow in either direction. The center of the galvanometer scale is zero. Current flow in one direction is indicated by deflection to the left of center. Current flow in the opposite direction is indicated by deflection to the right of center.

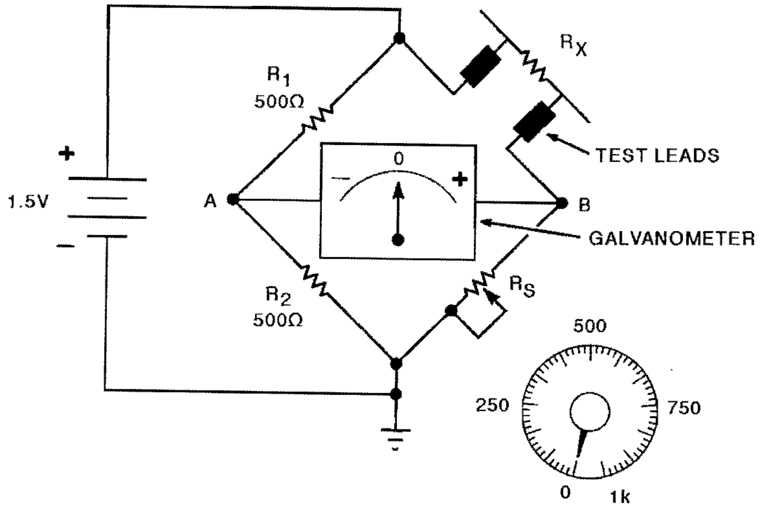


Figure 7-11
Wheatstone bridge.

To see how the bridge can be used to measure resistance, assume that a 210 Ω resistor is connected across the test leads. Remember R_1 and R_2 form a voltage divider which determines the voltage at point A. Since R_1 and R_2 are equal, the bridge is balanced only when R_X and R_S are also equal. Thus, R_S is set so that the galvanometer indicates exactly zero. At this point, the bridge is balanced so R_S must equal R_X. You can read this value directly from the calibrated dial of R_S. This gives you a simple method to find the value of an unknown resistor.

This simplified bridge can measure resistances up to 1 kΩ. In actual bridges, R_S is replaced with a device called a decade resistor box. Rotary switches allow you to set any value of resistance from a fraction of an ohm to several megohms. Thus, you can use the bridge to measure a wide range of resistances.

Self-Balancing Bridge

Another interesting application of a bridge circuit is shown in Figure 7-12. Here, the four resistors are replaced by two potentiometers. Also, the meter is replaced by a small DC motor (M). The motor turns anytime that the bridge is not balanced.

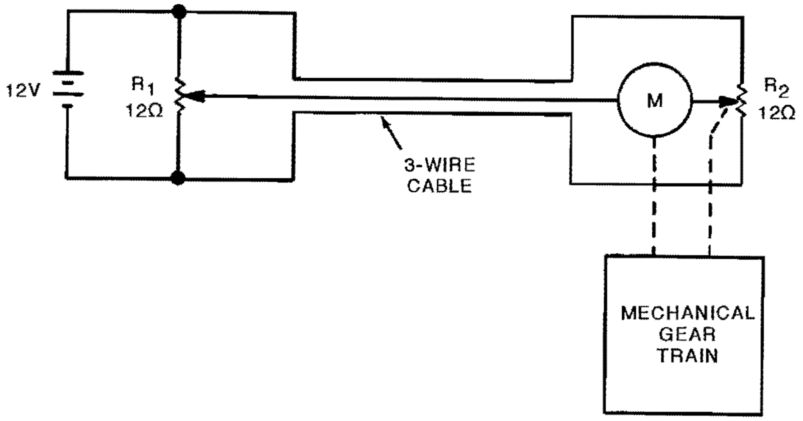


Figure 7-12
Self-balancing bridge.

This circuit is called a self-balancing bridge and can be used to control motion at a distance. For example, assume you have an antenna on a roof which you wish to turn from ground level. The motor and R_2 are located on the roof with the antenna. R_1 and the power supply are located at ground level. A 3-wire cable connects the two circuits together.

Assume that the circuit is initially balanced with the arms of both potentiometers set at the center position. Now if you wish to change the position of the antenna, you simply move the arm of R_1 to upset the balanced condition. This allows current to flow through the motor which causes the motor to turn. The motor is connected through a gear train to the antenna. Thus, as the motor turns, the antenna also turns. The motor is also connected to the arm of potentiometer R_2. The motor turns until the arm of R_2 is at the same relative position as the arm of R_1. This rebalances the circuit and the motor stops turning. The circuit allows you to control the position of a remote antenna simply by setting the arm of a potentiometer.

Temperature Sensing Bridge

If one of the resistors in a bridge circuit is replaced with a thermistor, the bridge can be used to indicate temperature. Figure 7-13 shows a temperature-sensing bridge.

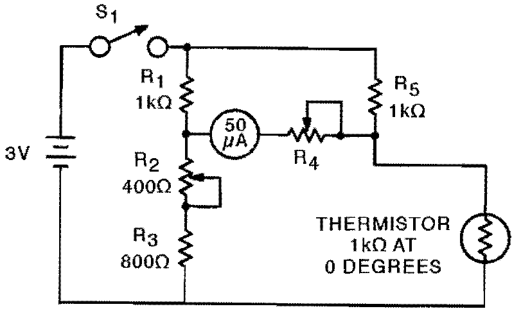


Figure 7-13
Temperature-sensing bridge.

R_1 and R_5 are 1 kΩ resistors. At 0 degrees, the thermistor also has a resistance of 1 kΩ. If R_2 is set to 200 ohms, the fourth arm of the bridge also has a resistance of 1 kΩ. Consequently, the bridge is balanced and no current flows through the 50 μA meter movement. Thus, the 0 μA point on the meter scale can be labeled 0 degrees.

As the temperature to which the thermistor is exposed increases, the resistance of the thermistor decreases. This upsets the balanced condition and causes current to flow through the meter. The higher the temperature goes, the more current flows through the meter. Thus, the current is an indication of the temperature. The meter scale can be marked off in degrees rather than microamperes.

R_4 is included to provide a means of calibrating the high end of the scale. For example, assume you wish the upper limit of the scale to be 100°. You expose the thermistor to a temperature of 100° and adjust R_4 for 50 μA of current through the meter movement. This causes full-scale deflection. Thus, the point of full-scale deflection is labeled 100°.

Programmed Review

24. A bridge circuit has two input terminals and two ____________ terminals.

25. (output) A bridge circuit is balanced when the voltage across the two output terminals is ____________ .

26. (zero) When the voltage across the output terminals is anything other than zero, the bridge is ____________ .

27. (unbalanced) The bridge circuit shown in Figure 7-8A is ____________ if all four resistors have the same value.

28. (balanced) However, all of the resistors do not need to be the same value to establish the balanced condition. Actually the circuit is balanced any time the following equation is satisfied.

$$\frac{R_1}{R_2} = \underline{\hspace{3cm}} .$$

29. $(\frac{R_3}{R_4})$

EXPERIMENT 17

Bridge Circuits

OBJECTIVES: *To demonstrate the characteristics of a bridge circuit.*

To verify that a balanced bridge satisfies the equation:

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

To build a Wheatstone bridge and demonstrate its operation.

To demonstrate two additional applications of a bridge circuit.

Introduction

Earlier you saw that the bridge is an extremely useful and important circuit. It is also fun to build and operate. In this experiment you will examine the construction, characteristics, and some uses of the bridge.

Material Required

1 — Heathkit Electronics Trainer
1 — Multimeter with test leads
1 — 100 Ω, 5%, 1/2-watt resistor (brown-black-brown-gold)
1 — 470 Ω, 5%, 1/2-watt resistor (yellow-violet-brown-gold)
1 — 10 kΩ, 5%, 1/2-watt resistor (brown-black-orange-gold)
1 — 15 kΩ, 5%, 1/2-watt resistor (brown-green-orange-gold)
1 — 68 kΩ, 5%, 1/2-watt resistor (blue-gray-orange-gold)
1 — 200 Ω, potentiometer (linear control) #10-917
1 — 1000 Ω, 5%, 1/2-watt resistor (brown-black-red-gold)
1 — Light dependent resistor (LDR), #9-83
1 — Thermistor (120 Ω), #9-34
1 — Thermistor (100 kΩ), #9-182
#22 copper (hook-up) wire

Procedure

1. Connect your voltmeter between the POS and GND terminals on the Trainer. Switch the Trainer ON and adjust the + voltage control until the voltmeter indicates 10 volts.

2. Switch the Trainer OFF and construct the circuit shown in Figure 7-14. Use the 1 kΩ potentiometer on the Trainer for R_2 and the 100 kΩ potentiometer on the Trainer for R_4. Make certain that the terminals of these pots are connected as shown. If the trainer you are using does not have numbered connector terminals arranged horizontally, assume the left (top) terminal to be #1; center #2; and right (bottom) #3.

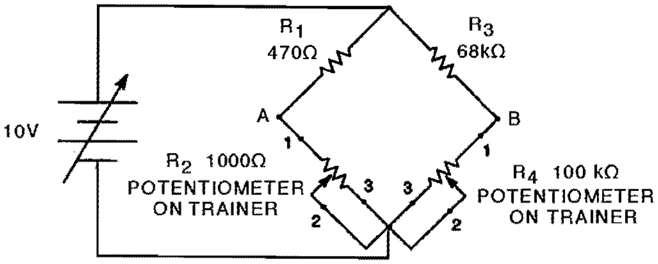


Figure 7-14
Basic bridge circuit.

3. Connect the positive lead of your voltmeter to point A in the circuit. Connect the negative lead of the voltmeter to the GND terminal of the Trainer. Switch the Trainer ON and adjust R_2 (the 1 kΩ potentiometer) until the voltmeter indicates exactly 4 volts.

4. In the same way, connect the voltmeter from point B to GND. Adjust R_4 (the 100 kΩ potentiometer) until the voltmeter indicates exactly 4 volts.

   NOTE: In the next step of this experiment you will measure the voltage between points A and B in your bridge circuit. In the previous two steps you set the voltage of these points to +4 volts *above* ground. Because points A and B are set to the *same* potential above ground, the voltage *between* these points should be zero, or very close to zero. You will make this measurement in the next step. As you learned earlier, in some bench-type meters, the negative (common) test lead is internally connected to earth ground via the third (ground) prong on its AC power cord. Connecting the common test lead of this kind of meter to *any* circuit point above ground causes a problem because it effectively shorts the circuit point to ground. This is shown in Figure 7-15. Fortunately, most meters are not this type, and of course, no battery-powered meter has the problem. If you are using a non-battery (line) type (bench) meter, make sure its common test lead is not earth grounded before you perform the remainder of this experiment.

If your meter reads near +4 volts instead of nearly zero when you perform the next step of this experiment, it has a grounded common test lead and cannot be used. If your meter's common test lead is earth grounded, keep this in mind when you make any circuit measurement in general.

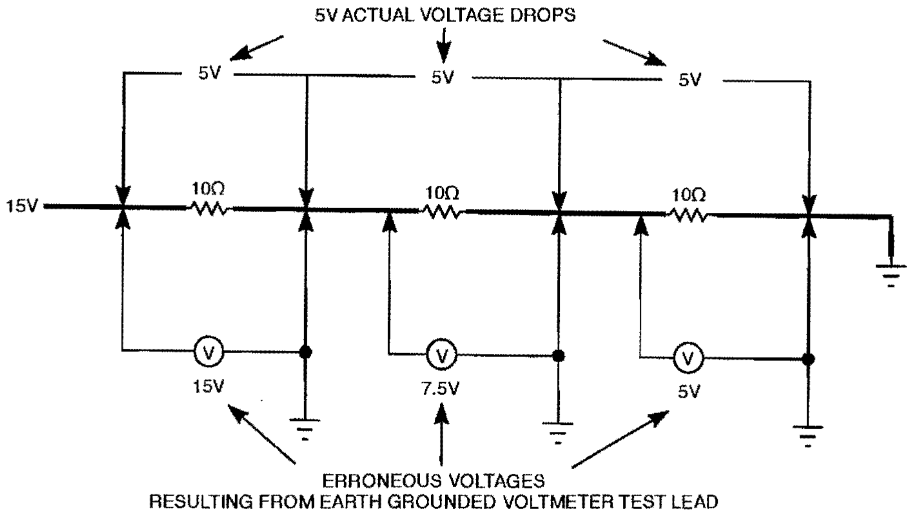

5V ACTUAL VOLTAGE DROPS
5V
5V
5V
15V
10Ω
10Ω
10Ω
V
V
V
15V
7.5V
5V
ERRONEOUS VOLTAGES
RESULTING FROM EARTH GROUNDED VOLTMETER TEST LEAD

Figure 7-15

Behavior of voltmeter with earth-grounded common test lead.

5. Now, connect the positive lead of the voltmeter to point A and the negative lead to point B. Set the voltmeter to its lowest voltage range* and adjust the 1 kΩ potentiometer (R_2) until the meter indicates exactly 0 volts. At this point the bridge is balanced.

6. Slowly adjust R_2 until the meter indicates slightly positive. To do this, you must turn R_2 ________________________.
   clockwise/counterclockwise

   This __________________ the resistance of R_2.
   increases/decreases

7. Slowly adjust R_4 until the meter once again indicates 0 volts. To do this, you must turn R_4 ________________________.
   clockwise/counterclockwise

   This __________________ the resistance of R_4.
   increases/decreases

---

* To measure the bridge output of balance you will generally need to set your voltmeter to its most sensitive scale — so be careful!

8. Slowly adjust R_2 until the meter indicates **slightly** negative (be very careful not to "peg" the needle if you are use an analog meter). To do this, you must turn R_2 ____________________ .
   clockwise/counterclockwise

   This _______________ the resistance of R_2.
   increases/decreases

9. Slowly adjust R_4 until the meter once again indicates 0 volts. To do this, you must turn R_4 ____________________ .
   clockwise/counterclockwise

   This _______________ the resistance of R_4.
   increases/decreases

10. Make certain that the bridge is balanced; that is, that the meter indicates exactly 0 volts. Remove the voltmeter's test leads from the bridge. Without touching the settings of R_2 and R_4, disconnect these from the circuit. Leave the wiper (#2) terminal jumpered to the end terminal (#3) of each pot.

11. Use the ohmmeter to measure the resistance between the unconnected end terminal (#l) and wiper (#2) terminal of the 1 kΩ potentiometer. R_2 = __________ ohms.

12. In the same way, measure the resistance between terminal #1 and the wiper (#2) terminal of the 100 kΩ potentiometer. R_4 = __________ kilohms.

13. Measure the values of R_1 and R_3. R_1 = __________ ohms, R_3 = __________ kilohms.

14. Substitute the measured values in the equation:

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

   Does the quantity R_1/R_2 closely agree in value with the quantity R_3/R_4? __________ .

Discussion

In Step 5, you adjusted R_2 until the voltmeter connected from points A to B indicated 0 volts to balance the bridge circuit. In Step 6 you increased the resistance of R_2 to upset the balanced condition. This caused the meter to indicate a positive voltage. In Step 7 you increased the value of R_4 in the same proportion to that of R_2 to rebalance the bridge.

In Step 8, you decreased the value of R_2 to again upset the balanced condition. This caused the meter to read a negative voltage. In Step 9, you reduced the value of R_4 to rebalance the circuit.

Finally, you disassembled the circuit and measured the values of the four resistors. Typical values are:

R_1 = 470 ohms

R_2 = 400 ohms

R_3 = 68 kilohms

R_4 = 60 kilohms

In this case, R1/R2 = 1.175 and R_3/R_4 = 1.133. Here, the ratio of R_1 to R_2 is within about 4 percent of the ratio of R_3 to R_4. This is about the best you can expect due to the inaccuracy of the ohmmeter. Your own values for R_2 and R_4 can vary greatly from the values given above. However, the ratio of R_1/R_2 should be within about 10 percent of the R_3/R_4 ratio.

One of the most practical applications of the bridge circuit is the Wheatstone bridge. It uses the resistance ratio described above to find the value of an unknown resistance. You will now investigate the Wheatstone bridge.

Procedure (Continued)

15. Construct the circuit shown in Figure 7-16A. Adjust the power supply to +5 volts across the bridge input as shown.

16. Connect your voltmeter (set to the 10 VDC or greater range) across the bridge output as shown. NOTE: If you use an analog meter, you may observe a slight needle deflection in the negative direction. If this occurs, adjust the 200 ohm potentiometer until you observe a small positive deflection.

17. While you observe the output voltage of the bridge on your voltmeter, adjust the 200 ohm pot to obtain zero volts out to balance the bridge. Be sure to orient the LDR so that it is exposed to a constant and unchanging amount of normal room light. You will notice the bridge become unbalanced if you shade (or further illuminate) the surface of the LDR. This is true, especially in the next step, when you fine-balance the bridge.

18. With your voltmeter set to its most sensitive voltage range, fine adjust the 200 ohm potentiometer to re-zero the bridge output. At this point, be careful not to greatly change the setting of the pot from its setting in the previous step. A large change in the pot's resistance would produce a voltage that exceeds the sensitive range to which your meter is now set.

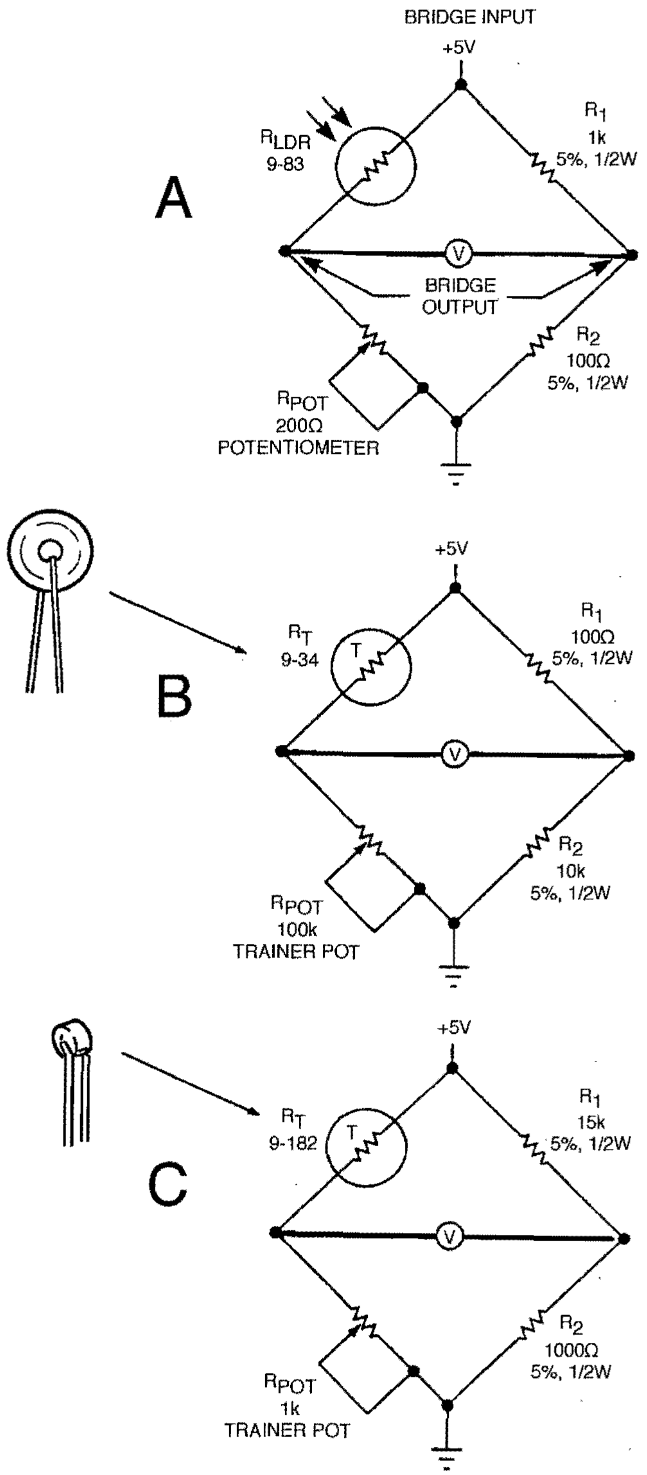

A
BRIDGE INPUT
+5V
R_{LDR}
9-83
R_1
1k
5%, 1/2W
V
BRIDGE
OUTPUT
R_2
100Ω
5%, 1/2W
R_{POT}
200Ω
POTENTIOMETER
B
+5V
R_T
9-34
T
R_1
100Ω
5%, 1/2W
V
R_2
10k
5%, 1/2W
R_{POT}
100k
TRAINER POT
C
+5V
R_T
9-182
T
R_1
15k
5%, 1/2W
V
R_2
1000Ω
5%, 1/2W
R_{POT}
1k
TRAINER POT

Figure 7-16
Wheatstone bridge circuits.

19. Be careful not to change either the setting of the pot or the orientation of the LDR while you remove the pot from the circuit. Measure its resistance.

R_{pot} = __________ ohms

20. Do not disturb the orientation or light exposure level of the LDR while you carefully remove the +5 volts power and ground jumper wire connections from the bridge. Remove both fixed resistors.

21. At this point, the LDR should be the only component that remains in your Trainer's breadboard. Do not disturb its orientation and avoid any unintentional changes in the amount of light on the LDR (compared to that present at bridge balance) while you carefully measure the resistance of the LDR.

R_{LDR} = __________ ohms

22. After you balanced the bridge, the voltage drops in the LDR/pot (series) bridge branch equaled the drops in the R_1/R_2 (series) branch. Hence, the voltage output of the bridge was zero. Mathematically,

$$\frac{E_{LDR}}{E_{pot}} = \frac{E_{R1}}{E_{R2}}$$

and because E = IR,

$$\frac{I_{LDR}R_{LDR}}{I_{pot}R_{pot}} = \frac{I_{R1}R_1}{I_{R2}R_2}$$

also, $I_{LDR} = I_{pot}$ (series); $I_{R1} = I_{R2}$ (series), so

$$\frac{R_{LDR}}{R_{pot}} = \frac{R_1}{R_2}$$

Since you know the values of R_{pot}, R_1, and R_2, you can solve for the unknown resistance of the LDR from the above equation as

$$R_{LDR} = \frac{R_1}{R_2} \times R_{pot}$$

Use this equation with your value of R_{pot} (recorded earlier) to calculate R_{LDR}. The calculated value of R_{LDR} is __________ ohms. Is this value approximately equal to your measured value? ______________

23. Use the 100 kilohm potentiometer on your Trainer to construct the circuit shown in Figure 7-16B .

24. Apply +5 V to the circuit and allow the thermistor to come to a constant (room) temperature. Measure the output voltage (most sensitive voltage scale) and adjust the pot as before to balance the bridge. Be careful not to touch the thermistor after you obtain a balance as your body heat will cause the thermistor resistance to decrease and throw the bridge out of balance.

25. Disconnect the circuit (as before) and measure the resistance of the pot, and thermistor at bridge balance. Record these values below.

R_{pot} = __________ ohms

R_T = __________ ohms

26. Use the values of R_1, R_2, and R_{pot} as before to calculate the thermistor resistance (R_T). Remember, R_1 now equals 100 ohms, and R_2 equals 10 kilohms.

R_T (CALC) = __________ ohms

27. Use the 1 kilohm potentiometer on your Trainer to construct the circuit shown in Figure 7-16C.

28. Apply +5V to the circuit and allow the thermistor to come to a constant (room) temperature. Measure its output voltage (most sensitive scale) and adjust the pot as before to balance the bridge. Be careful not to touch the thermistor after you obtain a balance as your body heat will cause the thermistor resistance to decrease and throw the bridge out of balance.

29. Disconnect the circuit (as before) and measure the resistance of the pot, and thermistor at bridge balance. Record these values below.

R_{pot} = __________ ohms
R_T = ________ohms

30. Use the values of R_1, R_2, and R_{pot} as before to calculate the thermistor resistance (R_T). Remember the new values for R_1 and R_2.

R_T (CALC) = ________

Does this value approximately equal your measured value? ____________

Discussion

In steps 15 through 22, you built, balanced, and used a Wheatstone bridge circuit to find the unknown resistance of a Light Dependent Resistor, or LDR. You checked the performance of the bridge by comparing the actual measured resistance of the LDR with your calculations of R_{LDR}. This part of the experiment assumed that you would be performing it with the LDR exposed to normal or typical average room lighting conditions. The actual value that you obtained depends upon the amount of light that the LDR was exposed to when you performed the experiment. You can expect the values to range from about 800 ohms (brighter rooms) to approximately 1400 ohms (darker rooms).

Be aware that the resistance of the LDR you worked with is very sensitive to even small changes in the light that it "sees." If you were very careful when you balanced your bridge and kept the light on the LDR at a constant level, you should have obtained "measured" and "calculated" results that are within at least 10% of each other (or better). If your results were more than 10% different, reperform this part of the experiment, and take care not to periodically shadow the LDR with your body. This can make a significant difference in your results.

In steps 23 through 30, you further used your basic Wheatstone bridge setup to determine the resistances of two different thermistor devices. You probably found that it was considerably easier to balance each of the thermistor bridge circuits than it was to balance the LDR bridge circuit. This is because these devices change their resistances in response to temperature, which is generally much more constant than localized lighting. Again, this part of the experiment assumed that you would be performing it at normal room temperature (68–72°F). Given this, typical resistance values for the thermistor resistances are 115 to 120 ohms (Figure 7-16B), and 95 kilohms to 100 kilohms (Figure 7-16C).

For each of the three bridge circuits you built, you used the last equation given in step 22 to calculate the value of the unknown bridge resistance, that is, R_{LDR} or R_T. This equation involves multiplying the resistance setting of a variable resistance (potentiometer) connected in series with the unknown resistance in one bridge branch, by the ratio of fixed resistances in the opposite bridge branch. Notice that the ratios of fixed resistances used were 10, 1/10, and 150 for the circuits in Figure 7-16A, B, and C respectively. Although these ratios were all either greater than, or less than one, you could construct a bridge circuit in which the ratio of these resistances *is* one. In a circuit of this type, the unknown resistance is simply equal to the resistance of the potentiometer when the bridge is balanced.

Finally, you should appreciate the potential application and usefulness of a Wheatstone bridge circuit by recognizing that it is the change in the resistance of a single bridge resistor that determines, not only that a voltage will develop across the output of the bridge, but also, the polarity of that voltage. This characteristic of the Wheatstone or resistor bridge is used in a large number of electronic instrumentation, sensing, and control applications.

KIRCHHOFF'S LAW

You can use the techniques described earlier to analyze many series-parallel circuits. However, you cannot always analyze more complex circuits with such simple methods. Often, a circuit will have several interconnected series-parallel branches and two or more voltage sources. Several techniques have been developed to help analyze circuits of this type. These techniques are generally grouped together under the name "network theorems."

A network is simply a circuit made up of several components such as resistors. Thus, the series-parallel circuits described earlier can be called networks. A network theorem is simply a logical method of analyzing a network. One of the most useful tools for analyzing a network is Kirchhoff's Law.

One form of Kirchhoff's Law was described earlier. It states the relationship between the voltage rises and the voltage drops around a closed loop in a circuit. Recall that the sum of the voltage drops is equal to the sum of the voltage rises. This fact is referred to as Kirchhoff's voltage law.

The voltage law is deceptively simple. At this point it is almost self-evident. Nevertheless, this law is a powerful tool when you use it properly. The next section describes it in more detail.

Kirchhoff's Voltage Law

The voltage law can be stated in several different ways. Up to now, it has been stated: *around a closed loop, the sum of the voltage drops is equal to the sum of the voltage rises*. Figure 7-17A illustrates this law.

Another way of saying the same thing is: *around a closed loop, the algebraic sum of all the voltages is zero*. It becomes apparent that this statement is true when you trace around the loop shown in Figure 7-17B. Notice that this is the same circuit as shown in Figure 7-17A. To keep the polarity of the voltages correct, it is helpful to establish a rule for adding the voltages. A convenient 3-part rule is:

1. Choose which direction you prefer to trace. (Clockwise or counterclockwise work equally well.)
2. Trace around the circuit in the direction you chose. If you encounter the positive side of a voltage drop (or voltage rise) first, consider that voltage drop (or rise) to be positive.
3. If you encounter the negative side of a voltage drop (or voltage rise) first, consider that voltage drop (or rise) to be negative.

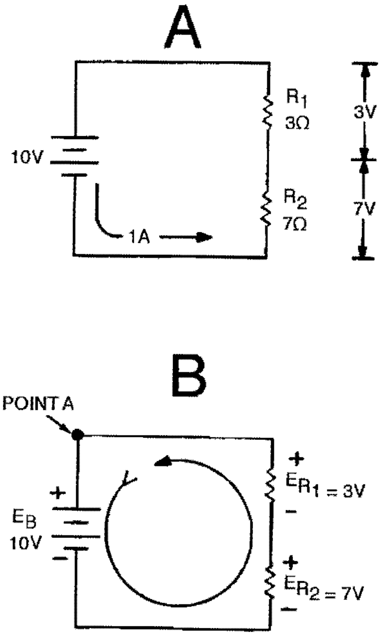


Figure 7-17
Kirchhoff's Voltage Law.

For example, start at point A in Figure 7-17B and trace counterclockwise as shown. Record each voltage you encounter. The first voltage is E_B. Because you encounter the positive side of the battery first, record the voltage as +10 V. You encounter E_{R2} next. You record this as –7 V because you arrive at the minus side first. You record E_{R1} as –3 V for the same reason. Thus, the sum of the voltages are:

$$+10\text{ V} - 7\text{ V} - 3\text{ V} = 0\text{ V}$$

Or stated as an equation:

$$E_B - E_{R2} - E_{R1} = 0\text{ V}$$

As you can see, the sum of the voltage drops around the loop is zero.

In this example, you arbitrarily traced around the loop in the counterclockwise direction. However, if you trace in the clockwise direction, you find that the sum is still zero.

How to Use Kirchhoff's Law

Look at the circuit shown in Figure 7-18A. You wish to find the current at all points in the circuit and the voltage that is dropped by each resistor. If you attempt to use only Ohm's Law to solve this problem, you run into insurmountable difficulties. However, if you use Kirchhoff's Law with Ohm's Law, you can easily find the solution.

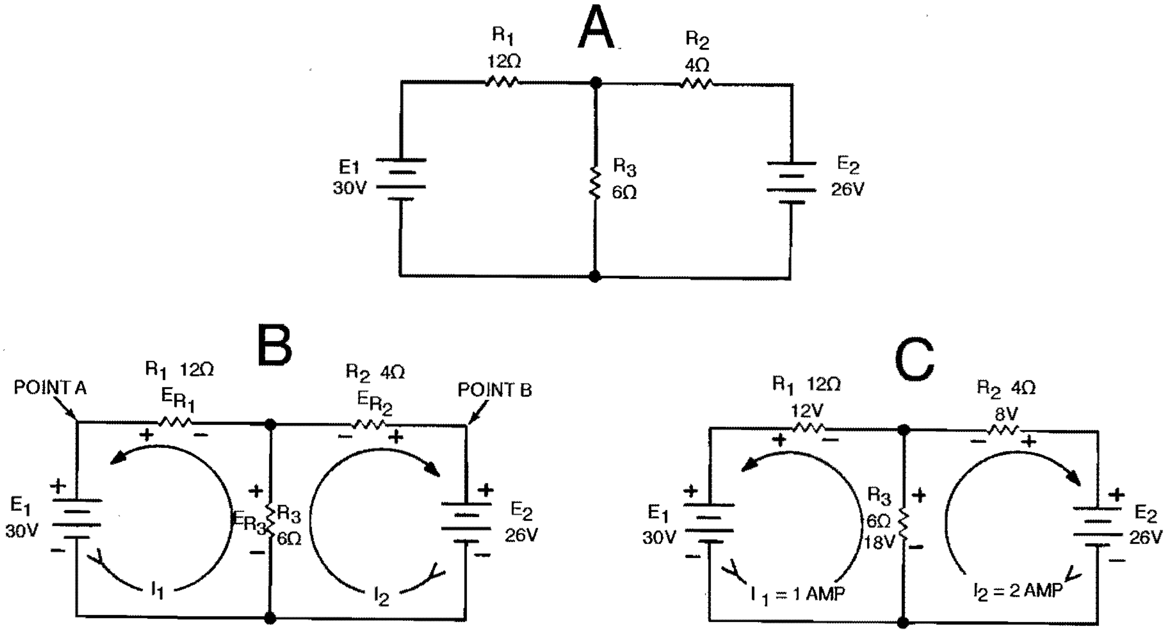

A
R1 12Ω
R2 4Ω
E1 30V
R3 6Ω
E2 26V
B
POINT A
R1 12Ω
ER1
R2 4Ω
ER2
POINT B
+
–
E1 30V
ER3
R3 6Ω
E2 26V
I1
I2
C
R1 12Ω
12V
R2 4Ω
8V
E1 30V
R3 6Ω 18V
E2 26V
I1 = 1 AMP
I2 = 2 AMP

Figure 7-18

How to use Kirchhoff's Law.

To apply Kirchhoff's Law the first step is to assume a direction of current through each loop. It makes no difference if your assumption is incorrect. The algebraic sign of your solution tells you if the direction you assumed is correct. For example, if your answer works out to + 3 amps, the direction you assumed is correct. If your answer works out to –3 amps, the direction you assumed is incorrect. A minus quantity of current indicates that the direction of current you assumed is reversed.

With the batteries connected as shown, it appears that the loop currents is in the direction shown by the arrow in Figure 7-18B. Assume that this is the direction of current flow.

The second step is to mark the polarity of the voltage drops across the resistors. To do this, mark negative polarity where current enters the resistor and positive polarity where current leaves the resistor. If you use this procedure with the direction of current flow you assumed in the previous paragraph, the polarity of voltage drops are marked as shown in Figure 7-18B.

The third step is to use Kirchhoff's voltage law to write an equation for each loop. To do this, you start at a given point and trace around the loop in the direction of current flow you assumed. You follow the procedure described earlier to record each voltage rise and voltage drop. Finally, you assume that the sum of all voltage drops and rises is equal to zero.

For example, trace out the loop through which I_1 flows. Start at the point labeled A in Figure 7-18B. Your equation becomes:

$$+E_1 - E_{R3} - E_{R1} = 0$$

Notice that you assume E_1 to be positive because you encounter its positive terminal. In the same way, you assume the voltage drops across R_3 and R_1 to be negative since you encounter their negative terminals. You can assume the sum of the three terms to be equal to zero in accordance with Kirchhoff's Law.

You can use this same procedure to develop an equation for the loop through which I_2 flows. If you start at point B and follow the direction of current flow you assumed, the equation becomes:

$$+E_2 - E_{R3} - E_{R2} = 0$$

At this point you have two equations which describe the operation of the circuit. They are:

$$E_1 - E_{R3} - E_{R1} = 0$$

$$E_2 - E_{R3} - E_{R2} = 0$$

Note that each equation contains a voltage rise and two voltage drops. The value of the voltage rises (E_1 and E_2) are given in Figure 7-18. If you substitute 30 volts for E_1 and 26 volts for E_2, your equations become:

$$30\ V - E_{R3} - E_{R1} = 0$$

$$26\ V - E_{R3} - E_{R2} = 0$$

The next step is to manipulate these equations so that you can use some of the other known values. Start with the equation:

$$30\ V - E_{R3} - E_{R1} = 0$$

The term E_{R1} is the voltage drop across R_1. Since this voltage drop is caused by I_1:

$$E_{R1} = R_1 \times I_1 = R_1I_1$$

Thus, the term R_1I_1 can be substituted for E_{R1} in our equation. The equation becomes:

$$30\ V - E_{R3} - R_1I_1 = 0$$

The term E_{R3} is the voltage drop across R_3. It is caused by currents I_1 and I_2. Thus:

$$E_{R3} = R_3 \times (I_1 + I_2) = R_3(I_1 + I_2)$$

By substitution, your equation becomes:

$$30\ V - R_3(I_1 + I_2) - R_1I_1 = 0$$

Next, you substitute the values of R_3 and R_1:

$$30\ V - 6(I_1 + I_2) - 12\ I_1 = 0$$

To eliminate the parentheses, multiply the –6 times each term within the parentheses:

$$30\ V - 6\ I_1 - 6\ I_2 - 12\ I_1 = 0$$

After you combine –6 I1 and –12 I1 you have:

$$30\ V - 18\ I_1 - 6\ I_2 = 0$$

At this point, it is convenient to have the voltage rise on one side of the equation and the voltage drops on the other. To do this, subtract 30 V from both sides of the equation. This leaves:

$$-18\ I_1 - 6\ I_2 = -30\ V$$

Now leave this equation for a moment and go back to the equation for the second loop. Recall that the equation is:

$$26\text{ V} - E_{R3} - E_{R2} = 0$$

If you treat this equation the same as you did the first, the steps look like this:

$$26\text{ V} - R_3(I_1 + I_2) - R_2I_2 = 0$$

Substitute values of R_3 and R_2:

$$26\text{ V} - 6(I_1 + I_2) - 4\,I_2 = 0$$

Remove parentheses:

$$26\text{ V} - 6\,I_1 - 6\,I_2 - 4\,I_2 = 0$$

Combine I_2 terms:

$$26\text{ V} - 6\,I_1 - 10\,I_2 = 0$$

Subtract 26 V from both sides:

$$-6\,I_1 - 10\,I_2 = -26\text{ V}$$

Thus, your two original equations have been changed to:

$$-18\,I_1 - 6\,I_2 = -30\text{ V}$$

$$-6I_1 - 10\,I_2 = -26\text{ V}$$

Note that each equation has two unknowns, I_1 and I_2. Equations of this type are called simultaneous equations. There are several methods of solving simultaneous equations. With one of the simplest methods, you cancel or eliminate one of the unknowns. This method works because of two simple facts:

1. You can do most anything you like to one side of an equation as long as you do the same thing to the other side. For example, you can add, subtract, multiply, or divide both sides of an equation by a number without upsetting the equality.

2. You can add two simultaneous equations together without upsetting the equality.

Consider your two simultaneous equations again:

$$-18\,I_1 - 6\,I_2 = -30\text{ V}$$

$$-6I_1 - 10\,I_2 = -26\text{ V}$$

You can multiply both sides of the bottom equation by –3 so that your equations become:

$$-\,18\,I_1 - 6\,I_2 = -\,30\text{ V}$$

$$+\,18\,I_1 + 30\,I_2 = +\,78\text{ V}$$

Note that by multiplying the bottom equation by – 3, you changed the term containing I_1 in the bottom equation to the same magnitude but opposite sign as the term containing I_1 in the top equation. If you now add the two equations, the I_1 terms cancel:

$$\begin{aligned} -\,18\,I_1 - 6\,I_2 &= -\,30\text{ V} \\ +\,18\,I_1 + 30\,I_2 &= +\,78\text{ V} \\ 0 + 24\,I_2 &= +\,78\text{ V} \end{aligned}$$

Thus, you end up with a single equation:

$$+\,24\,I_2 = +\,48\text{ V}$$

To solve for I_2, divide both sides of the equation by 24:

$$I_2 = \frac{+\,48}{+\,24} = +\,2\text{ amps}$$

Note that, because you divided a voltage by a resistance, the result is a current. This positive value of current tells you that the direction of current you assumed was correct. Now, to find I_1, substitute + 2 for I_2 in either of the above equations. That is:

$$-\,18\,I_1 - 6\,I_2 = -\,30\text{ V}$$

Substitute + 2 for I_2:

$$-\,18\,I_1 - 6\,(+2) = -\,30\text{ V}$$

$$-\,18\,I_1 - 12 = -\,30\text{ V}$$

Add 12 to both sides:

$$-\,18\,I_1 = -\,18\text{ V}$$

Divide by – 18:

$$I_1 = \frac{-\,18}{-\,18}$$

$$I_1 = +\,1\text{ amp}$$

Thus, the currents in the circuit are as shown in Figure 7-18C. Once you know the currents, you can use Ohm's Law to determine the voltage drops. When you compute the voltage drop across R_3 remember that both I_1 and I_2 flow through the resistor. Thus,

$$E_{R3} = R_3 (I_1 + I_2)$$

$$E_{R3} = 6\,\Omega\,(1\text{ A} + 2\text{ A})$$

$$E_{R3} = 6\,\Omega\,(3\text{ A})$$

$$E_{R3} = 18\text{ V}$$

Verify that the other voltage drops shown in Figure 7-18C are correct.

Kirchhoff's Current Law

Another form of Kirchhoff's Law involves current rather than voltage. You can state Kirchhoff's current law in several different ways. One form states that in parallel circuits, the total current is equal to the sum of the branch currents. Another way is that the current entering any point in a circuit is equal to the current leaving that same point. Figure 7-19 shows that this is simply two different ways of saying the same thing. Note that 1 ampere flows through each of two branches. Thus, the total current is 2 amperes. Now look at point A. Notice that 2 amperes flow into this point. Consequently, 2 amperes must flow out of this point. One ampere flows up through R_1 while the other ampere flows over and up through R_2. Once again, an important law is simply common sense. Nevertheless, you can use this simple law in much the same way as the voltage law to evaluate networks. However, because Kirchhoff's voltage law is generally easier to use, you will use the current law in this unit.

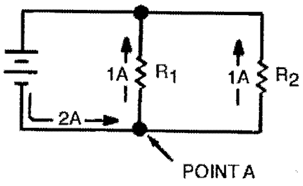


Figure 7-19
The current leaving point A is equal to the current entering point A.

Programmed Review

30. Figure 7-20 shows another network which you can solve with Kirchhoff's voltage law. Two loops are shown. Start at point A and trace clockwise around the first loop. The equation for this loop is: ______________ .

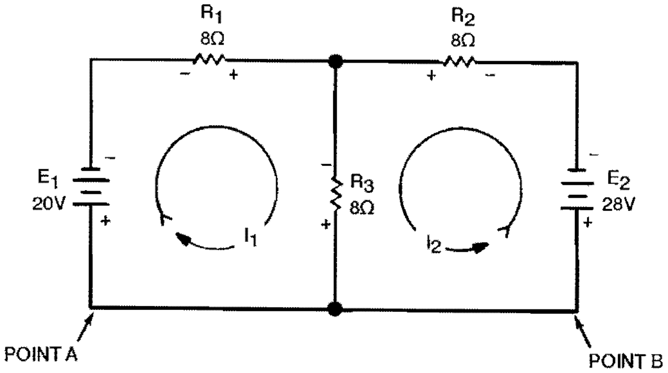


Figure 7-20

Solve with Kirchhoff's Law.

31. ($E_1 - E_{R1} - E_{R3} = 0$) E_1 is given as 20 V, E_{R1} is equal to 8 Ω times I_1. And E_{R3} is equal to 8 Ω times I_1 plus I_2. When you substitute these values, the equation becomes: ____________ .

32. ($20\ V - 8\ I_1 - 8(I_1 + I_2) = 0$) To get rid of the parentheses, multiply 8 times both I_1 and I_2. Thus, your equation becomes: ____________ .

33. ($20\ V - 8\ I_1 - 8\ I_1 - 8\ I_2 = 0$) After you combine like terms, the equation becomes: ____________ .

34. ($20\ V - 16\ I_1 - 8\ I_2 = 0$) Subtract 20 V from each side of the equation and you have: ____________ .

35. ($-16\,I_I - 8\,I_2 = -20$ V) Now go back and repeat this process for the second loop shown in Figure 7-20. Start at point B and trace in a counterclockwise direction. The original equation is: ____________.

36. ($E_2 - E_{R2} - E_{R3} = 0$) Substitute the values given and the unknown currents. The equation becomes: ____________.

37. ($28\text{ V} - 8\,I_2 - 8\,(I_1 + I_2) = 0$) Get rid of the parentheses. The equation is: ____________.

38. ($28\text{ V} - 8\,I_2 - 8\,I_1 - 8\,I_2 = 0$) Combine like terms. You get:

____________.

39. ($28\text{ V} - 8\,I_1 - 16\,I_2 = 0$) Subtract 28 V from each side of the equation. You have: ____________.

40. ($-8\,I_1 - 16\,I_2 = -28$ V) Compare this with the equation shown in parentheses in Frame 35. If the terms which contain I_1 in the two equations had the same magnitude but opposite sign, you could add the two equations together to cancel the I_1 terms. To can accomplish this, multiply the second loop equation by: ____________.

41. (-2) After you multiply the equation shown in Frame 40 by -2, you get:

____________.

42. ($+16\,I_1 + 32\,I_2 = +56$ V) Now, if you add this equation to the equation shown in Frame *35*, your work looks like this:

$$\begin{array}{r} -16\,I_1 - 8\,I_2 = -20\text{ V} \\ +16\,I_1 + 32\,I_2 = +56\text{ V} \\ \hline \end{array}$$

43. ($24 I_2 = 36$ V) Solve for I_2. You find that I_2 = ____________ .

44. ($I_2 = 1.5$ Amperes) You can now substitute the value of I_2 into the equation shown in Frame 35 and solve for I_1. Your work looks like this:

$$-16 I_1 - 8 I_2 = -20 \text{ V}$$

$$-16 I_1 - 8(1.5) = -20 \text{ V}$$

$$-16 I_1 - 12 = -20 \text{ V}$$

$$-16 I_1 = -8 \text{ V}$$

$$I_1 = \frac{-8}{-16}$$

I_1 =

45. ($I_1 = 0.5$ amperes) Once you know the two currents, you can solve for the voltage drops across the various resistors.

E_{R1} = ____________ ; E_{R2} = ____________ ; and

E_{R3} = ____________ .

46. ($E_{R1} = 4$ V; $E_{R2} = 12$ V; $E_{R3} = 16$ V)

SUPERPOSITION THEOREM

The superposition theorem is the most logical of the network theorems that you will study. This theorem is widely used in physics, engineering, and even economics. It is used to analyze systems in which several forces act simultaneously to cause a net effect. It gives you a simple logical method of determining the net effect.

The principle behind the superposition theorem is simple. To determine the net effect of several causes, find the individual effect of each cause acting alone and then add all of the individual effects together. For example, suppose you have two batteries which both force current to flow through a resistor. To determine the net current, find the individual currents caused by each battery and then add the individual currents together.

In more formal terms, the superposition theorem states: *In a linear, bilateral network containing more than one voltage source, the current at any point is equal to the algebraic sum of the currents produced by each voltage source acting separately.* So that the terms *linear* and *bilateral* do not cause confusion, you need to understand these terms. In a linear circuit, current is directly proportional to the voltage. If the voltage doubles, so does the current. Bilateral means the circuit conducts equally well in either direction. The resistive networks which you have been studying are both linear and bilateral, so they lend themselves to the superposition theorem.

The easiest way to see how this theorem works is to consider an example. Figure 7-21A shows a simple series circuit which contains two voltage sources and two resistors. The 50-volt battery attempts to force current in a counterclockwise direction while the 75-volt battery attempts to force current in a clockwise direction. The problem is to find the net current in the circuit.

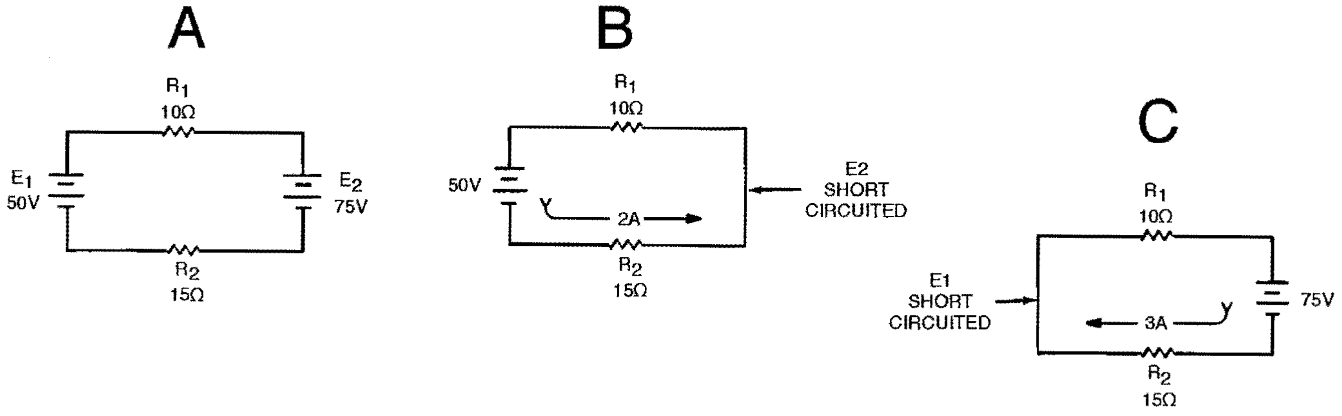


Figure 7-21
Using the superposition theorem.

The first step is to consider only the current produced by the 50-volt battery. To do this, you mentally short circuit the 75-volt battery. This leaves the circuit shown in Figure 7-21B. Here, the current is:

$$I = \frac{E}{R_T} = \frac{50\ \text{V}}{25\ \Omega} = 2 \text{ amperes}$$

This current flows in the counterclockwise direction as shown.

Next you consider the current produced by the 75-volt battery. You mentally short circuit the 50-volt battery as shown in Figure 7-21C. The current is:

$$I = \frac{E}{R_T} = \frac{75\ \text{V}}{25\ \Omega} = 3 \text{ amperes}$$

This current flows in the clockwise direction as shown.

As you can see, the 50-volt battery attempts to force 2 amperes in the counterclockwise direction. Simultaneously, the 75-volt battery attempts to force 3 amperes of current in the clockwise direction. Obviously then, the net current is 1 ampere in the clockwise direction.

Now consider a slightly more complex network. Figure 7-22A shows the circuit which you analyzed earlier with Kirchhoff's Law. Use the superposition theorem to find the currents in the various parts of the circuit.

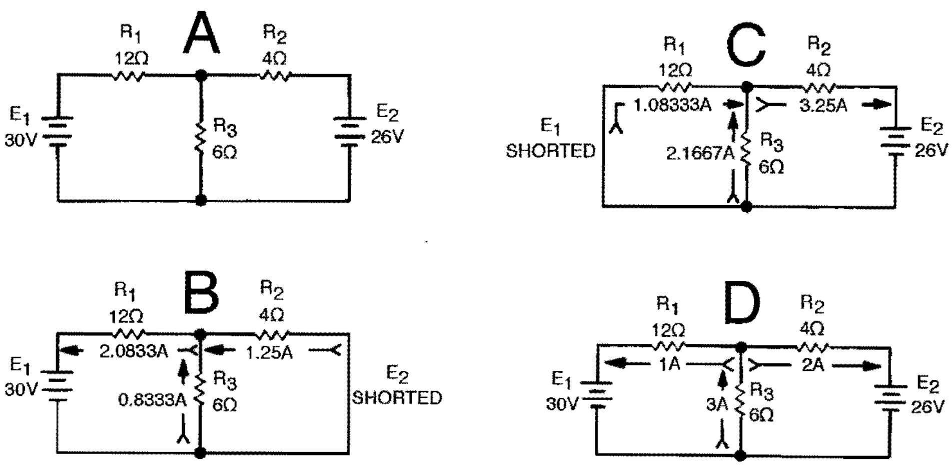

A
R1 12Ω
R2 4Ω
E1 30V
R3 6Ω
E2 26V
B
R1 12Ω
R2 4Ω
E1 30V
2.0833A
1.25A
0.8333A
R3 6Ω
E2 SHORTED
C
R1 12Ω
R2 4Ω
E1 SHORTED
1.08333A
3.25A
2.1667A
R3 6Ω
E2 26V
D
R1 12Ω
R2 4Ω
E1 30V
1A
2A
3A
R3 6Ω
E2 26V

Figure 7-22
Applying the superposition theorem
to a more complex network.

The first step is to redraw the circuit as shown in Figure 7-22B. Here, you are interested only in the current produced by E_1. Therefore, E_2 is shorted. The total resistance in this circuit is:

$$R_T = R_1 + \frac{R_2 \times R_3}{R_2 + R_3}$$

$$R_T = 12 + \frac{4 \times 6}{4 + 6}$$

$$R_T = 12 + \frac{24}{10}$$

$$R_T = 12 + 2.4$$

$$R_T = 14.4\,\Omega$$

Thus, the total current produced by E_1 is:

$$I = \frac{E_1}{R_T} = \frac{30\text{ V}}{14.4\,\Omega} = 2.08333 \text{ amperes.}$$

With this amount of current, the voltage drop across R_1 is:

$$E_{R1} = I \times R_1 = 2.08333\text{ A} \times 12\,\Omega = 25\text{ V}.$$

This leaves 5 V across R_2 and R_3. Thus, the current through R_2 is:

$$E_{R2} = \frac{E_{R2}}{R_2} = \frac{5\text{ V}}{4\,\Omega} = 1.25\text{ A}.$$

And, the current through R_3 is:

$$E_{R3} = \frac{E_{R3}}{R_3} = \frac{5\text{ V}}{6\,\Omega} = 0.8333\text{ A}.$$

Thus, the currents produced by E_1 are as shown in Figure 7-22B.

Next, you consider the currents produced by E_2 with E_1 shorted. The circuit is shown in Figure 7-22C. Here, the total resistance is:

$$R_T = R_2 + \frac{R_1 \times R_3}{R_1 + R_3}$$

$$R_T = 4 + \frac{12 \times 6}{12 + 6}$$

$$R_T = 4 + \frac{72}{18}$$

$$R_T = 4 + 4$$

$$R_T = 8\,\Omega$$

Thus, the total current is:

$$I_T = \frac{E_2}{R_T} = \frac{26\text{ V}}{8\,\Omega} = 3.25\text{ A.}$$

With this current, the voltage drop across R_2 is:

$$E_{R2} = I \text{ x } R_2 = 3.25\text{ A x } 4\,\Omega = 13\text{ V.}$$

This leaves 13 volts across R_1 and R_3. Thus, the current through R_1 is:

$$I_{R1} = \frac{E_{R1}}{R_1} = \frac{13\text{ V}}{12\,\Omega} = 1.08333\text{ A.}$$

Also, the current through R_3 is:

$$I_{R3} = \frac{E_{R3}}{R_3} = \frac{13\text{ V}}{6\,\Omega} = 2.1667\text{ A.}$$

Thus, the currents produced by E_2 are as shown in Figure 7-22C.

The final step is to superimpose the two circuits. In Figure 7-22B, the current through R_1 is 2.0833A flowing to the left. In Figure 7-22C, the current through R_1 is 1.08333A flowing to the right. Obviously then, the net current is 1A to the left. If you combine the other individual currents in the same way, you find the net currents are as shown in Figure 7-22D. Also, if you refer back to Figure 7-1 8C, you will see that these are the same values you computed earlier with Kirchhoff's Law.

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47. Figure 7-23A shows another network which you analyzed earlier with Kirchhoff's Law. To analyze this circuit with the superposition theorem, you first redraw the circuit as shown in Figure 7-23B. Here, the total resistance in the circuit is ____________ ohms.

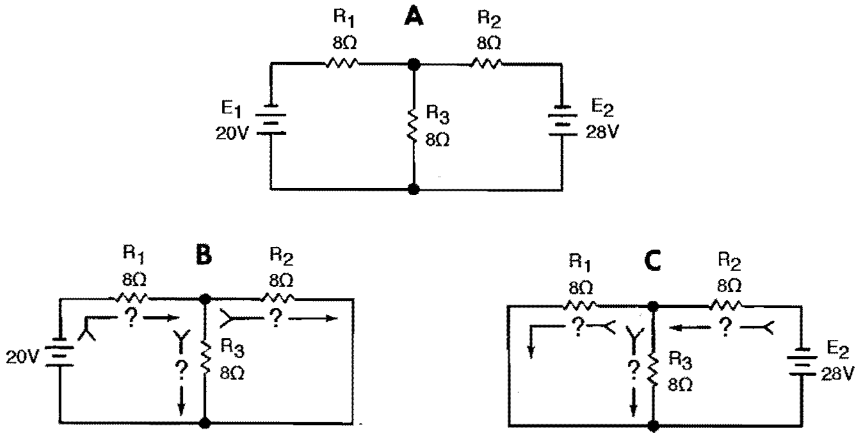

Figure 7-23
Analyze this network with the superposition theorem.

48. (12 ohms) Therefore, the total current in the circuit is ____________ amperes.

49. (1.667 amperes) This entire current flows through R_1, but is split evenly between R_2 and R_3. Thus, the current through R_2 is ____________ amperes.

50. (0.8333 amperes) Likewise the current through R_3 is ____________ amperes.

51. (0.8333 amperes) To determine the current produced by E_2, you redraw the circuit as shown in Figure 7-23C. Here, the total resistance is ____________ ohms.

52. (12 ohms) Therefore the total current is __________ amperes.

53. (2.333 amperes) This entire current flows through R_2, but is split evenly between R_1 and R_3. Thus, the current through R_3 is __________ amperes.

54. (1.1667 amperes) The current through R_1 is also 1.1667 amperes. Note that E_2 attempts to push 1.1667 amperes to the left through R_1 while E_1 attempts to push 1.667 amperes to the right through R_1. Thus, the net current through R_1 is __________ amperes to the __________ .

55. (0.5 amperes, right) The net current through R_2 is __________ amperes to the __________ .

56. (1.5 amperes, left) The net current through R_3 is __________ amperes.

57. (2.0 amperes) These are the same current values you computed earlier with Kirchhoff's Law.

THEVENIN'S THEOREM

Another important and powerful tool for simplifying and analyzing networks is Thevenin's theorem. Unlike the laws and theorems described earlier, the reason that Thevenin's theorem works is not at all obvious. Fortunately, you can use this theorem without understanding *why* it works.

This theorem allows you to replace any two-terminal network of voltage sources and resistors, no matter how they are interconnected, with a single voltage source in series with a single resistor. A two-terminal network is simply a network which has two output terminals. For example, you can replace the two-terminal networks such as those shown in Figure 7-24A with an equivalent circuit like the one shown in Figure 7-24B.

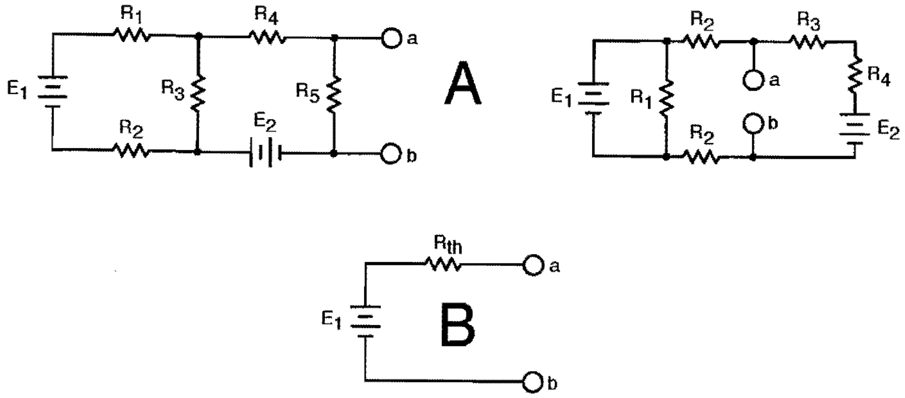

Figure 7-24
You can represent complex networks with a single voltage source (E_{th}) in series with a single resistor (R_{th}).

More formally, Thevenin's theorem states: *Any network of resistors and voltage sources, if viewed from any two terminals in the network, can be replaced with an equivalent voltage source (E_{th}) and an equivalent series resistance (R_{th}).* Of course, there are definite rules that concern the values you assign to E_{th} and R_{th}.

Perhaps the best way to understand this theorem is to consider an example. Figure 7-25A shows a simple circuit which you can easily analyze with Ohm's Law. In this example, R_3 is the load and the remaining circuitry is considered to be the source. Use Ohm's Law to determine the current through R_3. Do not read further until you calculate the value of I_{R3}. Now find the same current with Thevenin's theorem.

The first step is to mentally disconnect the load R3 from the rest of the circuit as shown in Figure 7-25B. Note that the circuit to the left of terminals a and b now has the same general form as those circuits shown in Figure 7-24A. Thus, you can replace this two-terminal network with a "Thevenin equivalent" like the one shown earlier in Figure 7-24B. The only problem is to find the proper value of E_{th} and R_{th}.

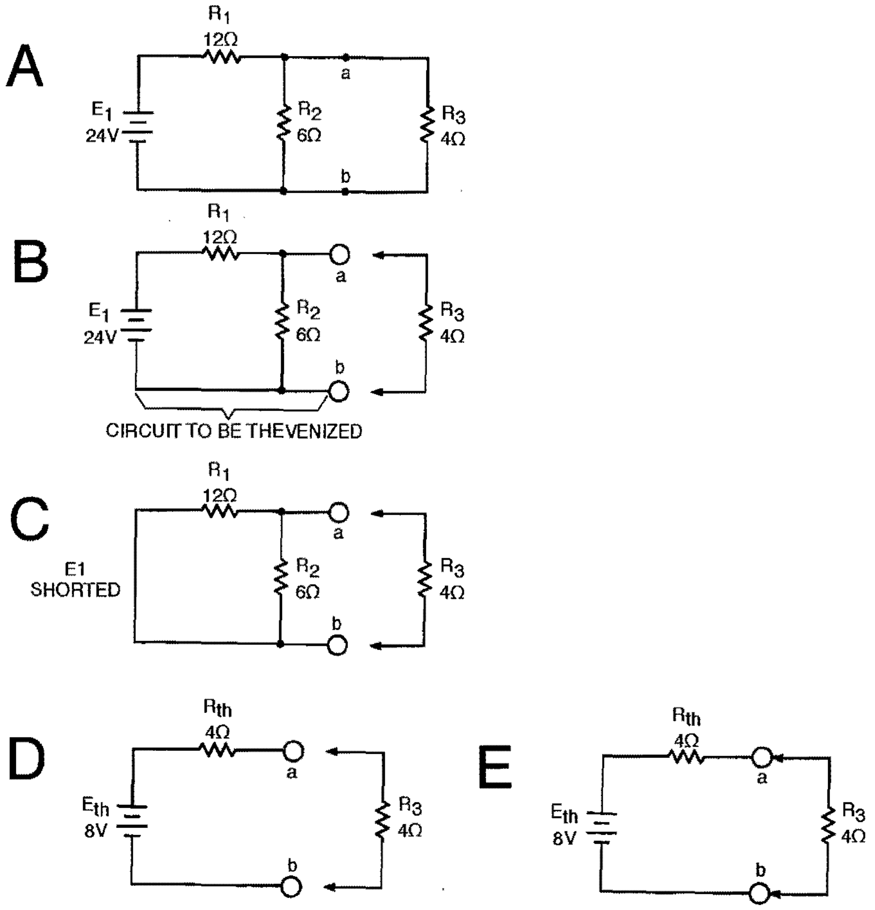
A
R1
12Ω
a
b
E1
24V
R2
6Ω
R3
4Ω
B
R1
12Ω
a
b
E1
24V
R2
6Ω
R3
4Ω
CIRCUIT TO BE THEVENIZED
C
R1
12Ω
a
b
E1
SHORTED
R2
6Ω
R3
4Ω
D
Rth
4Ω
a
b
Eth
8V
R3
4Ω
E
Rth
4Ω
a
b
Eth
8V
R3
4Ω

Figure 7-25
Using Thevenin's theorem.

Find E_{th} first. E_{th} is the voltage at points a and b when R_3 is disconnected as shown in Figure 7-25B. This is called the open circuit voltage. Remember, it is the voltage between points a and b when nothing is connected to these points except the circuit that is to be "thevenized." Since E_1, R_1, and R_2 now form a simple series circuit, you can easily compute the voltage between points a and b. First, you find the current in the circuit:

$$I = \frac{E}{R_T} = \frac{24\ \text{V}}{18\ \Omega} = 1.333 \text{ amperes.}$$

Note that the voltage between points a and b is the voltage drop across R_2 or E_{R2}. Thus, $E_{th} = E_{R2} = I \times R_2 = 1.333\ A \times 6\ \Omega = 8$ volts.

Now determine the value of R_{th}. R_{th} is the resistance between terminals a and b when the voltage source is shorted out. When E_1 is shorted as shown in Figure 7-25C, the resistance between a and b is:

$$R_{th} = \frac{R_1 \times R_2}{R_1 + R_2} = \frac{12 \times 6}{12 + 6} = \frac{72}{18} = 4\ \Omega.$$

Thus, you can represent the network shown in Figure 7-25B with the Thevenin equivalent shown in Figure 7-25D. Now reconnect R_3 between Terminals a and b as shown in Figure 7-25E. Note that the series parallel network has been redrawn as a simple series-equivalent circuit. You can now easily determine the current through R_3:

$$I = \frac{E}{R_T} = \frac{8\ V}{8\ \Omega} = 1 \text{ ampere.}$$

The current through R_3 is 1 ampere. This should be the same value which you computed with Ohm's Law.

You may wonder why Thevenin's theorem would be used at all on a simple circuit like that shown in Figure 7-25A. After all, you can find E_{R3} and I_{R3} with only Ohm's Law. However, there are times when this theorem is extremely valuable even with simple circuits like this one. Suppose for example, that you had to compute E_{R3} and I_{R3} for 100 different values of R_3. With only Ohm's Law, you would have to compute 100 different series-parallel problems. With Thevenin's theory you would still work one hundred problems. However, because the Thevenin equivalent would be the same for all of the problems, the problems would be the comparatively simple series-circuit type rather than the more complex series-parallel type.

This theorem also allows you to solve complex networks which cannot be analyzed with only Ohm's Law. For example, Figure 7-26A shows your old familiar problem again. You have already analyzed this circuit with Kirchhoff's Law and the superposition theorem. Now try Thevenin's theorem to see if you arrive at the same answers.

Find the current through R_3. You do this by thevenizing the entire circuit except for R_3. Thus, the first step is to open points a and b to remove R_3 from the circuit. The resulting circuit is shown in Figure 7-26B. Notice that in this circuit, E_1 tries to force current counterclockwise while E_2 tries to force current clockwise. The net voltage that causes current flow is $E_1 - E_2 = 30\ V - 26\ V = 4\ V$. The total resistance is $R_1 + R_2 = 12\ \Omega + 4\ \Omega = 16\ \Omega$. Thus, the current is $4\ V \div 16\ \Omega = 0.25$ amperes in the counterclockwise direction. Verify that the voltage drops across R_1 and R_2 are the polarity and magnitude shown.

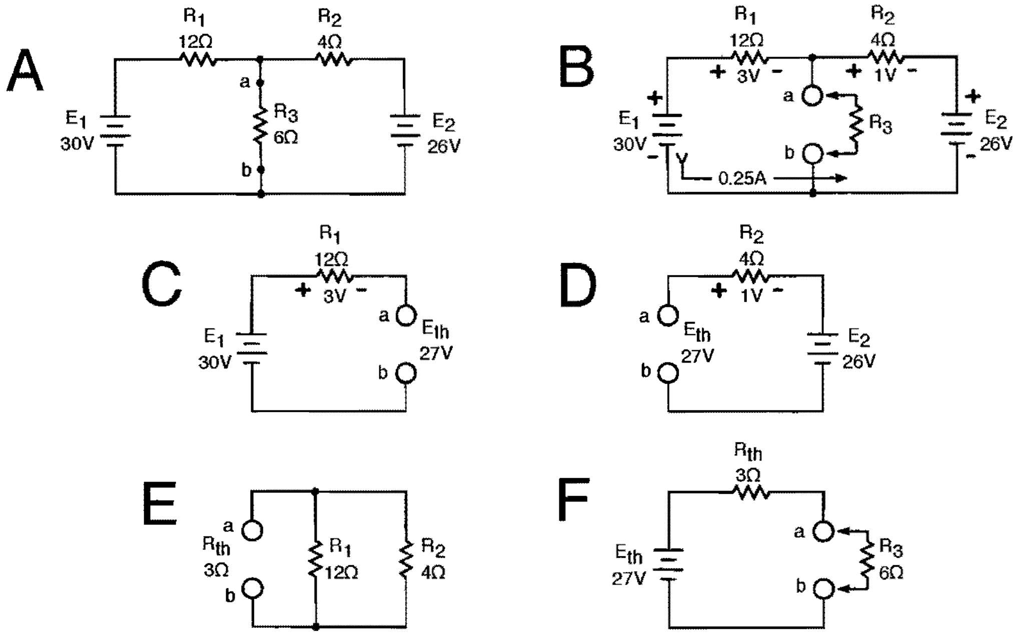
A
R1 12Ω
R2 4Ω
a
R3 6Ω
b
E1 30V
E2 26V
B
R1 12Ω
+ 3V -
R2 4Ω
+ 1V -
a
R3
b
E1 30V
0.25A
E2 26V
C
R1 12Ω
+ 3V -
E1 30V
a
Eth 27V
b
D
R2 4Ω
+ 1V -
a
Eth 27V
b
E2 26V
E
a
Rth 3Ω
b
R1 12Ω
R2 4Ω
F
Rth 3Ω
Eth 27V
a
R3 6Ω
b

Figure 7-26
Using Thevenin's theorem.

You can now determine Eth. Start at points a and b and look to the left. You see the circuit shown in Figure 7-26C. Note that the voltage between a and b is 30 V − 3 V = 27 V. You may wonder what value of E_{th} you would find if you look to the right of terminals a and b as shown in Figure 7-26D. The voltage is 1 V + 26 V = 27 V. Note that the value of E_{th} is the same because the two paths are in parallel.

Next, you determine the resistance between points a and b when the two voltage sources are short circuited to find R_{th}. As shown in Figure 7-26E, the resistance between points a and b is simply the value of R_1 and R_2 in parallel. Thus:

$$R_{th} = \frac{R_1 \times R_2}{R_1 + R_2} = \frac{12 \times 4}{12 + 4} = 3\ \Omega.$$

Thus, the Thevenin equivalent is the circuit shown in Figure 7-26F.

The final step is to reconnect R_3 to points a and b and determine the current:

$$I = \frac{E}{R_T} = \frac{27\ \text{V}}{9\ \Omega} = 3 \text{ amperes.}$$

This agrees with your earlier findings for the current through R_3.

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58. Figure 7-27A is a repeat of a circuit which we analyzed earlier using Kirchhoff's law and the superposition theorems. Using Thevenin's theorem let's find the current flowing through R_3. The first step is to disconnect ____________ from the circuit.

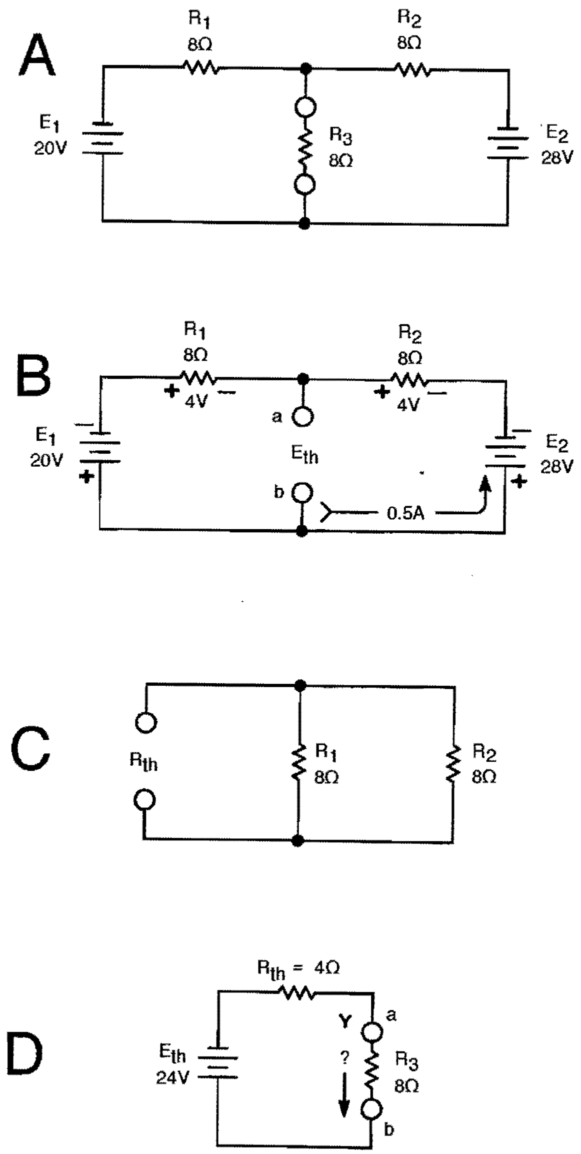
A
R1
8Ω
R2
8Ω
E1
20V
R3
8Ω
E2
28V
B
R1
8Ω
+ 4V −
R2
8Ω
+ 4V −
E1
20V
+
a
Eth
b
0.5A
E2
28V
+
C
Rth
R1
8Ω
R2
8Ω
D
Rth = 4Ω
Y
a
Eth
24V
?
R3
8Ω
b

Figure 7-27

Use Thevenin's Theorem to solve for I_{R3}.

59. (R_3) This leaves the circuit shown in Figure 7-27B. Because E_1 and E_2 oppose each other, the net voltage in the circuit is $E_2 - E_1 =$ ____________.

60. (8 volts) Because the total resistance is 16 ohms, the net voltages causes a current of ____________ amperes.

61. (0.5 amperes) Since E_2 has a higher voltage than E_1, the current flows in a ____________ direction.

62. (counterclockwise) R_1 drops ____________ volts. So does R_2.

63. (4 volts) Look at the circuit on the left side of terminals a and b. When you examine the voltages shown, you find that E_{th} is ____________ volts.

64. (24 volts) Examine the voltage in the circuit to the right of terminals a and b. Again you find that E_{th} is ____________ volts.

65. (24 volts) Next you short circuit E_1 and E_2 to find R_{th}. This leaves the circuit shown in Figure 7-27C. Thus, $R_{th} =$ ____________ ohms.

66. (4 ohms) The circuit shown in Figure 7-27A reduces to the Thevenin equivalent shown in Figure 7-27D. This allows you to determine the current through R_3. This current is ____________ amperes.

67. (2 amperes) Also, the voltage drop across R_3 is ____________ volts.

68. (16 volts) Verify that these are the values you computed earlier for this same circuit.

NORTON'S THEOREM

With Thevenin's theorem, you found that a circuit like that in Figure 7-28A can be represented by the equivalent circuit in Figure 7-28B. Norton's theorem gives you a slightly different way of representing the same circuit. Thevenin's theorem uses an equivalent *voltage* source (E_{th}) in *series* with an equivalent resistance (R_{th}). On the other hand, Norton's theorem uses an equivalent *current* source (I_N) in *parallel* with an equivalent resistance (R_N). Thus, the circuit in Figure 7-28A can also be represented by the Norton equivalent shown in Figure 7-28C.

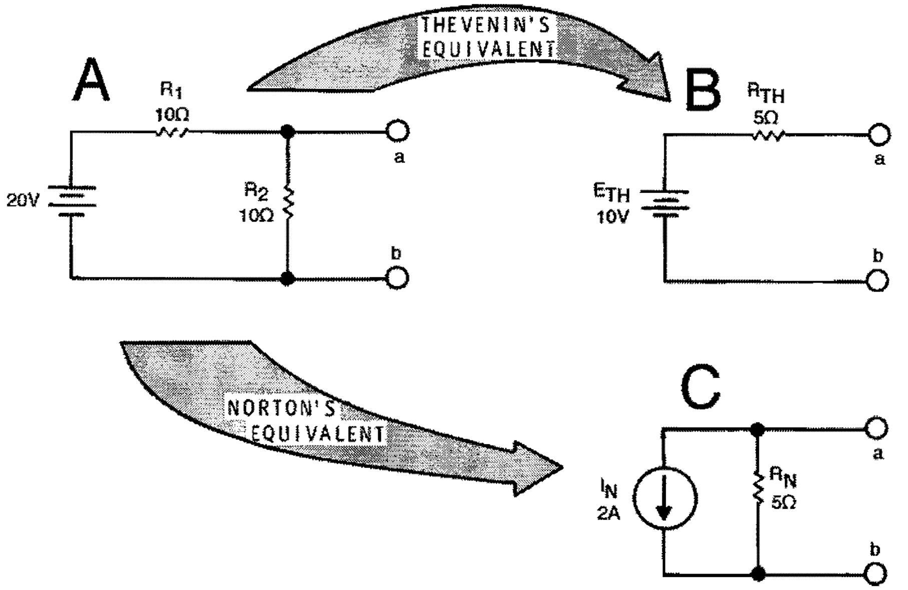

Figure 7-28
Comparing Norton's and
Thevenin's equivalent circuits.

Current Sources and Voltage Sources

At this point some words of explanation are in order. The idea of a voltage source is easy to visualize. An ideal voltage source is a device which produces the same output voltage regardless of the current drawn from it. In most electronic devices, you can consider a battery as a nearly ideal voltage source. A large 12-volt battery produces an output of approximately 12 volts whether the load current is 0 amperes, 1 ampere, or even 10 amperes. The reason for this is that the resistance of the battery is very low compared to the load resistance connected to it. An ideal voltage source would have an internal resistance of 0 ohms. In most electronic devices, the internal resistance of the battery or power supply is negligible compared to other circuit resistances. Thus, you can generally consider a battery as a nearly ideal voltage source. In Thevenin's theorem, E_{th} is considered to be an ideal voltage source which has 0 ohms resistance.

The idea of a current source is similar. Whereas a voltage source has a certain voltage rating, the current source has a certain current rating. An ideal current source will deliver its rated current regardless of what value of resistance is connected across it. Figure 7-28 illustrates this point. The voltage source (E_{th}) in Figure 7-28B produces exactly 10 volts regardless of what resistance value is connected across terminals a and b. In the same way, the current source in Figure 7-28C produces 2 amperes regardless of the resistance value that is connected across terminals a and b.

You can visualize a current source as a voltage source with an enormously high internal resistance. Consider, for example, the circuit shown in Figure 7-29. Here, a 10-volt battery is shown in series with a 1 megohm resistor. If points a and b are shorted, the current in the circuit is:

$$I = \frac{E}{R} = \frac{10\ V}{1{,}000{,}000\ \Omega} = 10\ \mu A.$$

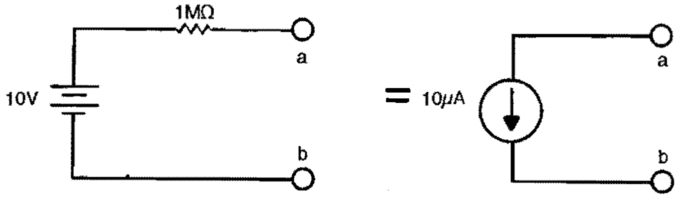

Figure 7-29
The current source.

If you connect a 10 Ω resistor between a and b, the current will still be 10 μA for all practical purposes. Even a 1 kΩ resistor would not cause a noticeable drop in current. Thus, this circuit acts as a 10 μA current source. Of course, this is not an ideal current source because if you connect a large enough resistance between points a and b, the current will decrease. An ideal current source would have an infinite resistance and the current output would be constant regardless of the load resistance.

Note that the symbol for the current source is a circle with an arrow. In this course, the arrow points in the direction of electron flow through the current source.

Finding the Norton Equivalent

Norton's theorem allows you to *represent* a circuit that contains voltage sources and resistors as a current source (I_N) in parallel with an equivalent resistance (R_N). Thus, although an ideal current source is impossible to build, you can represent the most simple or the most complex circuit as if it were an ideal current source and a parallel resistor. As with Thevenin's theorem, there are strict rules that tell you what the values of I_N and R_N must be to represent a specific circuit.

The value of the current source (I_N) is equal to the current which flows through the terminals of the network when they are shorted. As an example, refer back to Figure 7-28A. To convert this circuit to its Norton equivalent you first short together terminals a and b to determine the short circuit current. Note that doing this shorts out R_2. Thus, the total resistance in the circuit is the 10 ohms of R_1. Consequently, the value of the current source is:

$$I_N = \frac{E}{R} = \frac{20\text{ V}}{10\,\Omega} = 2 \text{ amperes.}$$

The size of the parallel resistor (R_N) is equal to the resistance between terminals a and b when the voltage sources are shorted. Thus, in Figure 7-28A, the resistance is R_1 and R_2 in parallel or 5 ohms. Note that the methods you use to find the resistor value is the same in both Thevenin's and Norton's theorems. The difference is that in the case of Norton's theorem, the resistor is in parallel with the current source. When you use these rules, the circuit in Figure 7-28A reduces to the Norton equivalent in Figure 7-28C.

With nothing connected between terminals a and b, the entire 2 amperes flow through R_N. However, if you connect a load resistor between terminals a and b, the current splits between R_N and the load resistor. The amount of current that each resistor conducts is inversely proportional to its resistance. If the load resistor has the same value as R_N, each passes 1 ampere. If the load resistor is larger, it passes proportionately less current.

Figure 7-30A is a repeat of the circuit which you evaluated with each of the network theorems. To illustrate Norton's theorem, use it to solve for the current through R_3. Since you are interested in the current through R_3, you wish to find a Norton equivalent for the circuit which connects to R_3.

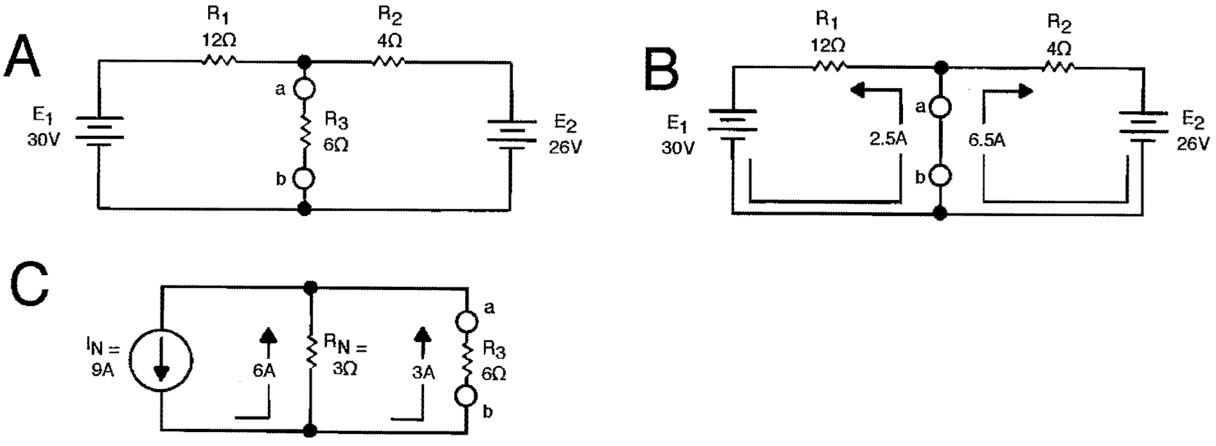

Figure 7-30
Using Norton's theorem.

To find the current source (I_N), you must imagine a short circuit across terminals a and b as shown in Figure 7-30B. The current from b to a that is caused by E_1 is:

$$I = \frac{E_1}{R_1} = \frac{30\ \text{V}}{12\ \Omega} = 2.5\ \text{A}.$$

Also, E_2 causes a current to flow from b to a:

$$I = \frac{E_2}{R_2} = \frac{26\ \text{V}}{4\ \Omega} = 6.5\ \text{A}.$$

Thus, the total current from b to a is 2.5 + 6.5 = 9 A. This is the value of the current source (I_N) as shown in Figure 7-30C.

Next you find the shunt resistance (R_N). To do this, you mentally short E_1 and E_2 and measure the resulting resistance. Obviously, the resistance is equal to R_1 and R_2 in parallel. Thus:

$$R_N = \frac{R_1 \times R_2}{R_1 + R_2}$$

$$R_N = \frac{12 \times 4}{12 + 4} = \frac{48}{16} = 3\ \Omega$$

Thus, you can redraw the circuit shown in Figure 7-30A as shown in Figure 7-30C. Note that everything except R_3 has been reduced to I_N and R_N.

Finally, to find the current through R_3 you determine how the 9A from the current source is distributed between R_N and R_3. Obviously, R_N draws more of the current since it is smaller. In fact, R_N draws twice as much current since it is one-half the size of R_3. Thus, two-thirds of the current flows through R_N while only one-third flows through R_3. The current through R_N is 2/3 x 9 A = 6 A while the current through R_3 is 1/3 x 9 A = 3 A. A handy equation for finding the current through R_3 is:

$$I_{R3} = \frac{R_N}{R_N + R_3} \times I_N = \frac{3}{3 + 6} \times 9 = \frac{3}{9} \times 9 = 3\ \text{A}$$

You use this equation to determine how the current (I_N) is distributed between the two resistors (R_N and R_3). While this equation is especially useful when you apply Norton's theorem, you can use it to determine the current distribution between any two parallel resistors.

The procedure ends when you find that 3 amperes of current flow through R_3. Earlier, you solved this same problem in other ways and arrived at the same answer.

Norton-Thevenin Conversions

It has probably occurred to you that there are striking similarities between Norton's theorem and Thevenin's theorem. Norton's theorem represents a circuit as a current source and a shunt resistor, while Thevenin's theorem represents the same circuit as a voltage source in series with the same value resistor. Since you can represent a given circuit in either form, there must be some way of converting directly from a Norton equivalent to a Thevenin equivalent and vice versa.

Figure 7-31A shows a two-terminal network which you can represent as the Thevenin equivalent shown in Figure 7-31B or as the Norton equivalent in Figure 7-31C. To convert the Thevenin form directly to the Norton form, simply apply Norton's theorem to the Thevenin equivalent circuit. If you short points a and b, the current is:

$$I_N = \frac{E_{th}}{R_{th}} = \frac{6\ V}{4\ \Omega} = 1.5\ A$$

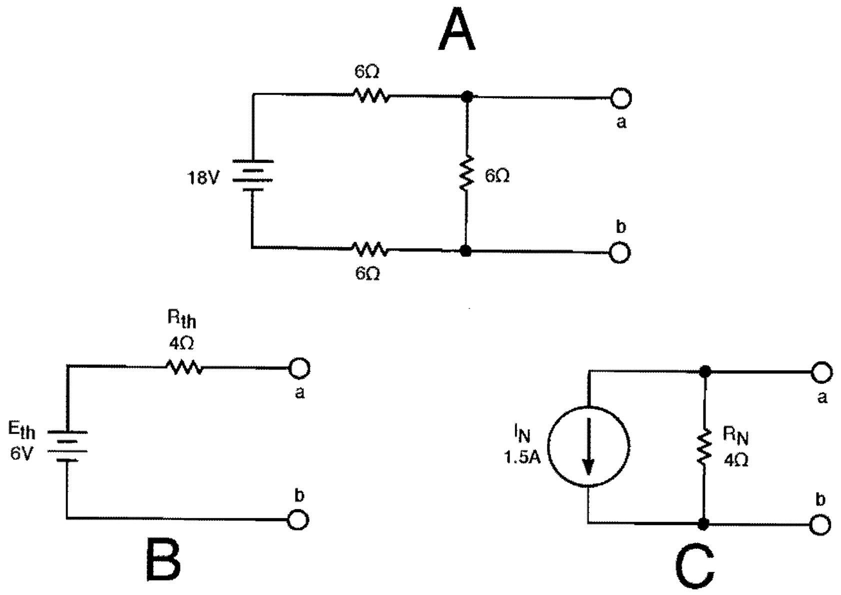

Figure 7-31

Norton-Thevenin conversions.

Next, you short out E_{th} and measure the resistance between points a and b to find R_N. Obviously, R_N is the same as R_{th}. Thus, you derive the Norton equivalent shown in Figure 7-31C.

Conversion in the opposite direction is just as easy. You simply apply Thevenin's theorem to the Norton equivalent. The open circuit voltage between a and b is:

$$E_{th} = I_N \times R_N = 1.5\ A \times 4\ \Omega = 6\ V$$

Now, to find R_{th}, you must know how to handle a current source. Recall that an ideal voltage source has 0 resistance and, thus, is replaced with a short when you find R_{th} or R_N. However, as you saw, an ideal current source has infinite resistance. Thus, when you find R_{th} or R_N, you consider a current source as an open circuit. Thus, if you open the current source, the resistance between points a and b is 4 ohms. As before: $R_{th} = R_N$.

To summarize, you can apply two simple equations to convert from the Thevenin form to the Norton form:

$$I_N = \frac{E_{th}}{R_{Th}} \text{ and } R_N = R_{th}$$

Likewise, you can apply these equations to convert from the Norton form to the Thevenin form:

$$E_{th} = I_N \times R_N \text{ and } R_{th} = R_N$$

The other thing you must remember is that in the Thevenin form, R_{th} is in series while in the Norton form, R_N is in shunt.

Programmed Review

69. With Norton's theorem, a two-terminal network is represented by a __________ source and an equivalent resistance.

70. (current) The equivalent resistance (R_N) is always in __________ with the current source.
series/parallel

71. (parallel) Whereas an ideal voltage source has 0 resistance, an ideal current source has __________ resistance.

72. (infinite) The value of the current source is the current which flows through the terminals when they are __________ .
shorted/open

73. (shorted) You determine the size of R_N with the same method you used to find R_{th} with __________ theorem.

74. (Thevenin's) Now use Norton's theorem to solve for the current through R_3 in the circuit shown in Figure 7-32A. The first step is to short out R_3 and determine the current from point a to b as shown in Figure 7-32B. The current produced by E_1 is __________ .

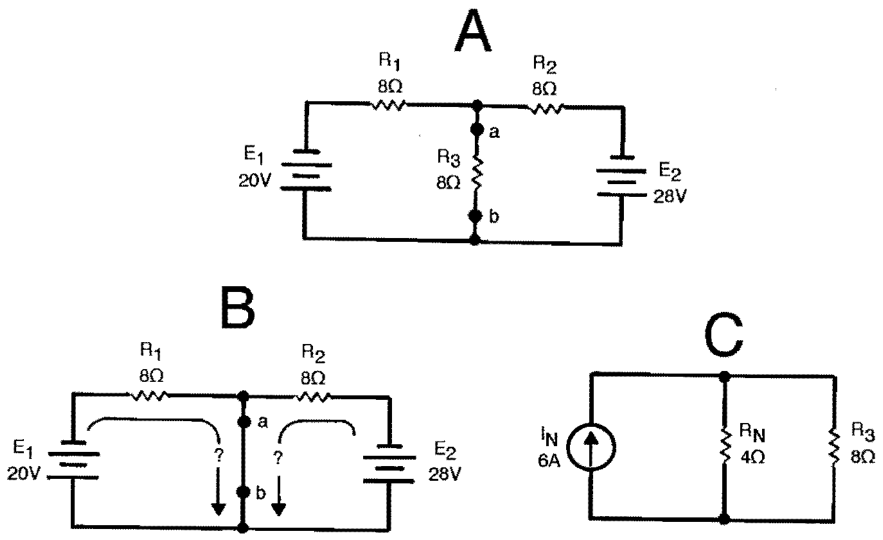

Figure 7-32

Use Norton's theorem to solve for I_{R3}.

75. (2.5 A) The current caused by E_2 is ___________ .

76. (3.5 A) Thus, the value of the current source (I_N) is ___________ .

77. (6 A) The value of R_N is ___________ .

78. (4 Ω) Thus, you can redraw the circuit as shown in Figure 7-32C. The 6 A is distributed between R_N and R_3. You can use this equation to determine the current through R_3:

I_{R3} = ___________ .

79. $\left(\frac{R_N}{R_N + R_3} \times I_N\right)$

Thus, the current through R_3 is ___________ .

80. (2 A) You used other theorems to solved this same problem earlier. Verify that this answer is correct.

81. Sometimes it is useful to be able to convert from a Norton equivalent to a Thevenin equivalent. To do this, you use the two equations ___________ and ___________ .

82. ($E_{th} = I_N \times R_N$ and $R_{th} = R_N$) Also, you can use these two equations to convert from a Thevenin form to a Norton form: ___________ and ___________ .

83. ($I_N = \frac{E_{th}}{R_{th}}$ and $R_N = R_{th}$).

EXPERIMENT 18

Network Theorems

OBJECTIVES: *To verify the superposition theorem.*
To verify Thevenin's theorem.
To verify Norton's theorem.

Introduction

With this experiment, you will verify three of the most common network theorems. In the first part of the experiment, you will construct and make measurements on a circuit to confirm the superposition theorem. Next, you will make measurements on a Thevenized version of the same circuit. Finally, you will apply the principles of Norton's Theorem to measure the circuit. You will compare the results of all three measurement methods to their calculated values, as well as, to each other.

Material Required

1 — Heathkit Analog Trainer
1 — Multimeter with test leads
2 — 1000 ohm, 5%, 1/2-watt resistors (brown-black-red-gold)
1 — 1000 ohm, 1%, 1/2-watt resistor (brown-black-black-brown-brown)
#22 copper hook-up) wire

Procedure

1. Switch the Trainer ON and connect your voltmeter between the +POS and GND terminals of your Trainer. Then adjust the voltage control to +10 volts.

2. Connect your voltmeter between the –NEG and GND terminals of your Trainer. Then adjust the voltage control to –5 volts. Note: Be sure to respect polarity if you use an analog meter.

3. Switch the Trainer OFF and connect the circuit shown in Figure 7-33. Set your meter to measure current between 1 and 5 mA.

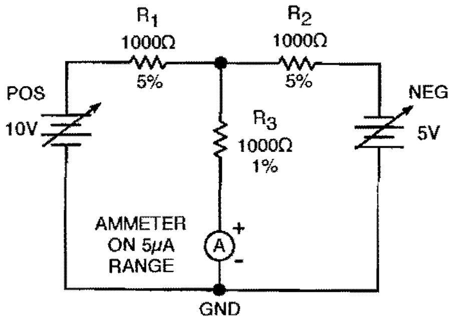

Figure 7-33

Circuit to verify the superposition theorem.

4. Switch the Trainer ON. Then measure and record the current through R_3. I_3 = ____________ mA.

5. Note that the +10V supply pushes current up through R_3 while the –5V supply attempts to push current down through R_3. Do these currents aid or oppose each other? __________ .
(aid/oppose)

6. Disconnect the jumper wire from the –NEG terminal of the Trainer and insert it into ground. This effectively "shorts out" the –NEG supply to the circuit. Does this increase or decrease the value of I_3? ______________ .
(increase/decrease)

With the –NEG supply "shorted" I_3 = ____________ mA.

7. Remove the grounded jumper (from Step 6) from the GND terminal of the Trainer and reconnect it to the –NEG terminal. The current returns to ____________ mA.

8. To protect your analog meter from reversed currents, set your meter to its highest current range. Disconnect the jumper wire from the +POS terminal of the Trainer and insert it into the GND terminal. This effectively "shorts out" the +POS supply to the circuit. Observe your meter when you do this. The direction of current (compared to before) as indicated by your meter is ______________ .
(the same/reversed)

9. If you are using an analog meter, interchange the leads to measure current in the opposite direction (compared to step 4). Readjust your meter to measure in the 2 to 20 mA range. Measure and record the current through R_3. I_3 = ____________ mA. This is a negative current, compared to the current measured in step 4. You should place a – (negative sign) in front of it to designate it as such.

10. You saw that the +POS supply by itself attempts to force +____________ mA through R_3. Also, the negative supply (alone) attempts to force –____________ mA through R_3 (in the opposite direction). Thus, the net current is:

    +____________ mA –____________ mA = ____________ mA.

    Is this net current approximately the same as the current you measured in step 4? Which network theorem does this verify? ____________ .

Discussion

In the first part of this experiment, you verified the superposition theorem. The net current through R_3, which you measured in step 4, should be about 1.67 mA. By "shorting out" the negative power supply, you found that the positive supply forces about +3.34 mA through R_3. When you shorted out the positive supply, the negative supply forced about –1.67 mA through R_3 (in the opposite direction). Thus, the net current you calculated in step 10 should be about +3.34 mA –1.67 mA = +1.67 mA. There should be close agreement between the current you measured in step 4 and the current you calculated in step 10. If you use the superposition theorem to further calculate the current, you should obtain the following results:

Negative Circuit Supply Shorted

R_2 in parallel with R_3 = 500 ohms; this is in series with R_1, so the total resistance R_T = 1500 ohms, and, the total current, I_T = 10 V/1500 ohms, or +6.67 mA. Because this divides equally between R_2 and R_3, $I_2 = I_3 =$ **3.34 mA.**

Positive Circuit Supply Shorted

R_1 in parallel with R_3 = 500 ohms; this is in series with R_2, so the total resistance R_T = 1500 ohms, and, the total current, I_T = –5 V/1500 ohms, or –3.34 mA. Because this divides equally between R_1 and R_3, $I_1 = I_3 =$ **–1.67 mA.**

Net Current Through R_3

$$I_3 = +3.34 \text{ mA} - 1.67 \text{ mA} = +1.67 \text{ mA}$$

Your calculations with the superposition theorem should agree closely with your measurements.

Procedure (Continued)

11. Construct the circuit shown in Figure 7-34A. Set your positive and negative power supply voltages as precisely as possible to the voltages indicated. Now use Thevenin's theorem to determine E_{th}, R_{th}, and I_3. Record your calculated values in the spaces provided.

    E_{th} = __________ V R_{th} = __________ ohms I_3 = __________ mA

    Next you will measure E_{th}, R_{th}, and I_{th}.

12. Removing R_3 to open the circuit at points a and b. Connecting your voltmeter between points a and b as shown in Figure 7-34B to measure E_{th}. E_{th} __________ V.

13. Although the theoretical application of Thevenin's theorem requires voltage sources to be shorted out to calculate R_{th}, when you work with real circuits it is seldom (if ever) a good idea to "dead short" a power supply output! Fortunately, there is a simple way to accomplish the same effect. Look at the circuit you constructed on the Trainer breadboard. It should still be connected as shown in Figure 7-34B. Now make three modifications to this circuit:

    A. Disconnect the wire from the +POS terminal and connect it to the ground terminal.

    B. Disconnect the wire from the negative supply terminal and connect it to the ground terminal.

    C. Reset your meter to measure resistance in the hundreds-of-ohms range.

    Your circuit should now look (schematically) like Figure 7-34C. In this figure, the circuit points previously connected to the supply terminals, are now connected to ground. This emulates shorting the supplies without adversely affecting them. In general, you should never short directly across the output terminals of a live power supply.

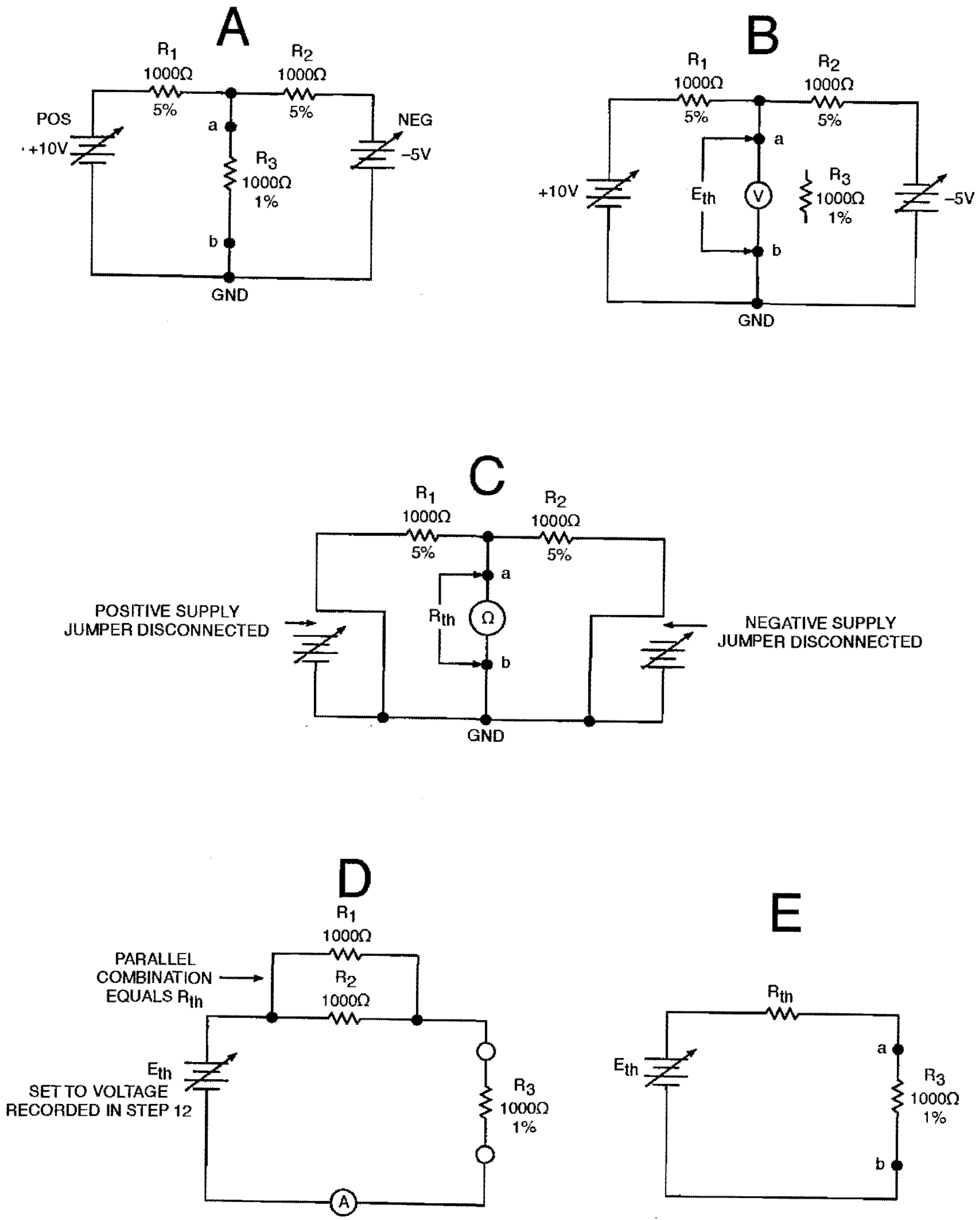
A
R1
1000Ω
5%
R2
1000Ω
5%
POS
+10V
a
R3
1000Ω
1%
NEG
–5V
b
GND
B
R1
1000Ω
5%
R2
1000Ω
5%
a
+10V
Eth
V
R3
1000Ω
1%
–5V
b
GND
C
R1
1000Ω
5%
R2
1000Ω
5%
a
POSITIVE SUPPLY
JUMPER DISCONNECTED
Rth
Ω
NEGATIVE SUPPLY
JUMPER DISCONNECTED
b
GND
D
R1
1000Ω
PARALLEL
COMBINATION
EQUALS Rth
R2
1000Ω
Eth
SET TO VOLTAGE
RECORDED IN STEP 12
R3
1000Ω
1%
A
E
Rth
a
Eth
R3
1000Ω
1%
b

Figure 7-34
Circuits to verify Thevenin's theorem.

14. Study your circuit and its schematic in Figure 7-34C. You are now measuring the ____________ resistance of R_1 and R_2. The resistance, R_{th}, measures =
(series/parallel)
____________ ohms. Disconnect your ohmmeter from the circuit.

15. Use the E_{th} and R_{th} values you measured to construct the Thevenin equivalent circuit as shown in Figure 7-34D. Set the positive supply voltage to the E_{th} value you measured in step 12. Note that the single Thevenin resistance R_{th} is represented by the parallel combination of R_1 and R_2. With your meter set to measure current in the 5 mA range, measure the current through the circuit as shown. This is the current through R_3, or I_3. I_3 = __________ mA. Is this measured value close to the value calculated in step 11? ________.
(yes/no)

Is the measured value I_3 in step 15 close to that measured in step 4? ________.
(yes/no)

Discussion

In this part of the experiment you verified Thevenin's theorem by measurement. In step 12 you measured E_{th}. If your voltage settings were precise, and your components were within tolerance, you should have seen about 2.5 V as the Thevenin voltage, E_{th}. Your measurement of R_{th} in step 14 should have been the parallel value of R_1 and R_2, or about 500 ohms. In step 15 you measured the current through R_3. You should have measured about 1.67 mA as I_3. These measured values should have closely agreed with your calculated values from Step 11.

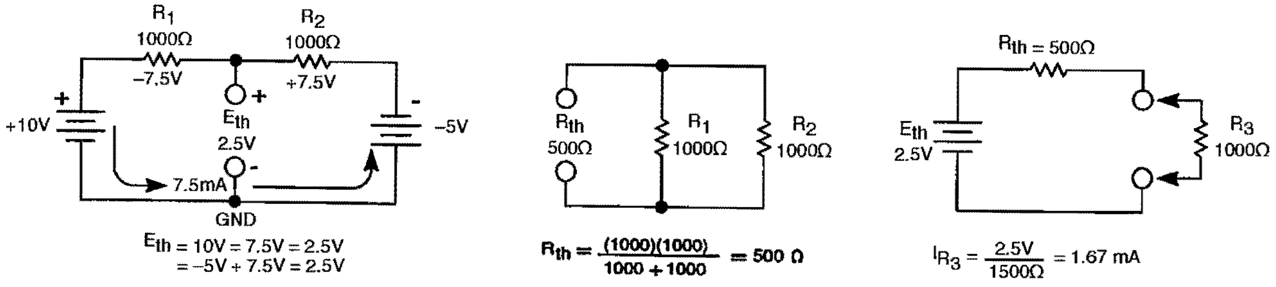

Figure 7-35

Note the voltage drop across R_1 and the voltage rise across R_2 to obtain E_{th}. Unlike the previous examples, the supplies are connected in a series-aiding configuration. The same basic circuit will also be used to verify Norton's theorem.

Procedure (Continued)

16. Reconfigure the circuit as shown in Figure 7-36A. This time you will use Norton's theorem to solve for the current through R_3.

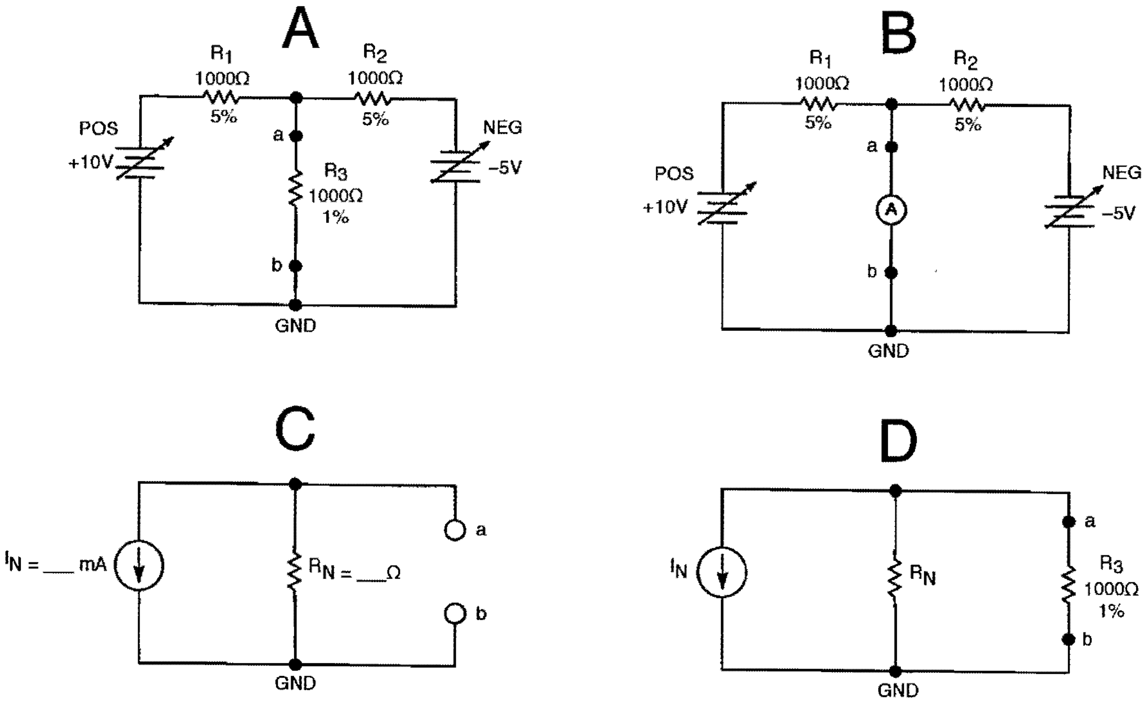
A
R_1 1000Ω 5%
R_2 1000Ω 5%
POS +10V
NEG −5V
a
R_3 1000Ω 1%
b
GND
B
R_1 1000Ω 5%
R_2 1000Ω 5%
POS +10V
NEG −5V
a
A
b
GND
C
I_N = ___ mA
R_N = ___ Ω
a
b
GND
D
I_N
R_N
a
R_3 1000Ω 1%
b
GND

Figure 7-36

Circuits to verify Norton's theorem.

17. Remove R_3 to open the circuit at points a and b. Connect your meter to measure the current flow between points a and b as shown in Figure 7-36B. Recall that ammeters have a very low resistance, thus, points a and b are essentially shorted together through the meter. As a result, the current you measure with the meter is the short circuit current or Norton current, I_N. Record its value, I_N = ____________ mA. Switch the Trainer OFF.

18. Because the Norton resistance R_N is the same as R_{th} you measured earlier in step 14, R_N = ____________ ohms.

19. Figure 7-36C shows the Norton equivalent circuit. Fill-in the values of I_N and R_N. If you now reconnect R_3 between terminals a and b, the Norton current (I_N) will split according to the formula:

$$I_3 = \left(\frac{R_N}{R_N + R_3}\right) \times I_N$$

Thus, the calculated value of I_3 is __________ mA. Does this agree with the values you calculated and measured for this current previously? ________ .
(yes/no)

Discussion

In step 17 you determined that I_N is about 5 mA. Also, R_N is the same as the value of R_{th} you measured earlier and found to be 500 ohms. In step 19, you found that the 5 mA split so that 1/3 of it flows through R_3 while 2/3 flows through R_N. Thus, once again you found that I_3 is about 1.67 mA. You used the principles of Norton's theorem to thereby verify its use experimentally.

In conclusion, this experiment has allowed you to examine three of the most widely used network theorems in basic electronics. The main principles of each theorem were applied to the same circuit for comparison purposes. Although each method should yield the same results, you may find that one or more of these three methods may be easier to apply than the other(s) to analyze certain kinds of problems. Also, remember that these theorems are primarily used as circuit analysis techniques. They were simply verified (experimentally) here. You should make sure that you know how to apply each of the theorems for circuit analysis problems that involve more than one voltage, or current, source.

SUMMARY

In a series circuit, you add the individual resistance values to find the total resistance:

$$R_T = R_1 + R_2 + R_3 + \ldots$$

The current is the same at all points in the circuit and the sum of the voltage drops is equal to the applied voltage.

In parallel circuits, the total resistance is less than that of any branch. With two branches:

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

With more than two branches:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots}$$

The voltage is the same across all of the branches and the total current is the sum of the branch currents.

You can usually combine resistors with one or more of the above formulas to reduce simple series-parallel circuits to simpler forms.

A voltage divider produces two or more output voltages from a common higher voltage.

A series dropping resistor controls the value of current and voltage that is applied to a load.

A bridge circuit generally consists of four resistances connected together so that there are two input terminals and two output terminals. You can select resistor values so that the bridge is balanced. In this condition, the voltage between the two output terminals is 0. You can use the bridge with a meter to measure resistance or temperature.

Kirchhoff's law provides a way to analyze circuits which you cannot analyze with Ohm's Law alone. Kirchhoff's voltage law states that the sum of the voltages around a closed loop is 0. When a circuit has two or more loops, you can write an equation for each loop. You can then combine the equations in such a way that only one unknown is left. The unknown quantity can therefore be determined. Kirchhoff's current law states that the current that enters a point is equal to the currents that leaves that point. You can also use it to analyze complex circuits.

The superposition theorem gives you a logical way to analyze circuits which have more than one voltage source. You consider the effect of each voltage source one at a time with all of the other voltage sources shorted out. You then combine the individual effects to determine the net effect of all of the voltage sources.

Thevenin's theorem is a handy tool for analyzing networks because it allows you to represent a complex two-terminal network as a single voltage source in series with a single resistor.

Norton's theorem is equally handy because it allows you to represent a complex two-terminal network as a single current source in parallel with a single resistor.

UNIT EXAMINATION

1. Refer to Figure 7-37. The proper value for R_2 is:

    A. 2.5 ohms.
    B. 7.5 ohms.
    C. 3.33 ohms.
    D. 10 ohms.

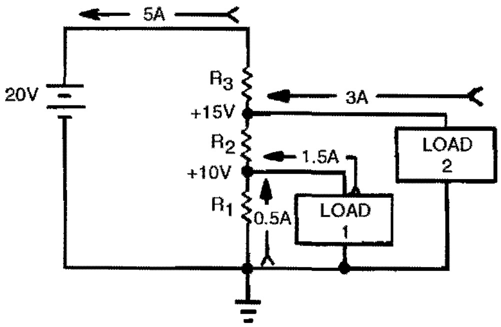

Figure 7-37
Circuit for Questions 1 and 2.

2. Refer to Figure 7-37. The proper value for R_3 is:

    A. 1.66 ohms.
    B. 4 ohms.
    C. 5 ohms.
    D. 1 ohm.

3. A 4-volt relay is to be used with a 12-volt power supply. If the relay requires a current of 0.1 ampere, what value of series dropping resistor is required?

    A. 40 ohms.
    B. 80 ohms.
    C. 120 ohms.
    D. 20 ohms.

4. Refer to Figure 7-38. Which Figure shows a bridge circuit that is not balanced?

   A. Figure 7-38A.
   B. Figure 7-38B.
   C. Figure 7-38C.
   D. Figure 7-38D.

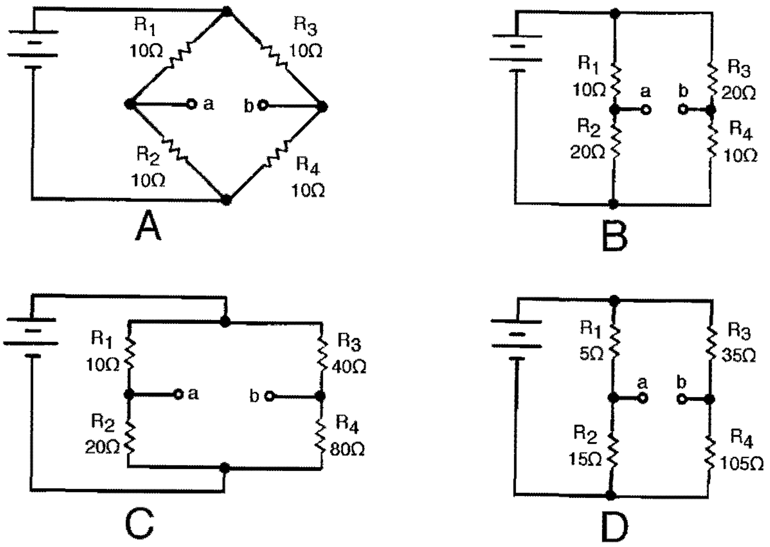
R1
10Ω
R3
10Ω
a
b
R2
10Ω
R4
10Ω
A
R1
10Ω
a
b
R3
20Ω
R2
20Ω
R4
10Ω
B
R1
10Ω
R3
40Ω
a
b
R2
20Ω
R4
80Ω
C
R1
5Ω
R3
35Ω
a
b
R2
15Ω
R4
105Ω
D

Figure 7-38
Circuits for Question 4.

5. Refer to Figure 7-39. To balance this bridge circuit, you should:

   A. move the arm of R_1 up.
   B. move the arm of R_2 down.
   C. move the arm of R_2 up.
   D. do nothing because the bridge is presently balanced.

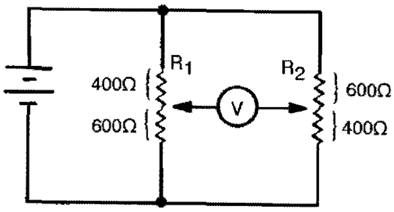
R1
R2
400Ω
600Ω
V
600Ω
400Ω

Figure 7-39
Circuit for Question 5.

6. Use Kirchhoff's voltage law to analyze the circuit shown in Figure 7-40. What is the current through R_3?

   A. 1.5 A.
   B. 2.5 A
   C. 1 A.
   D. 4 A.

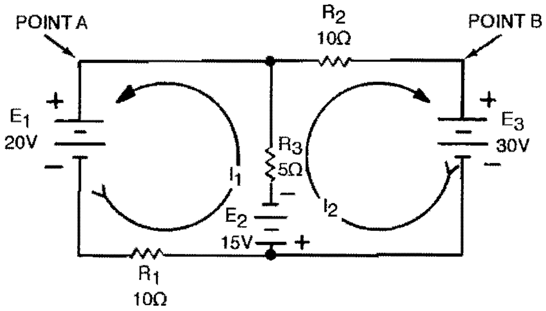
POINT A
R2
10Ω
POINT B
+
E1
20V
−
+
E3
30V
−
R3
5Ω
I1
I2
E2
15V
−
+
R1
10Ω

Figure 7-40
Circuit for Question 6.

7. Use the superposition theorem to analyze the circuit shown in Figure 7-41. What is the voltage drop across R_1?

   A. 1.667 volts.
   B. 3.333 volts.
   C. 5.0 volts.
   D. 6.667 volts.

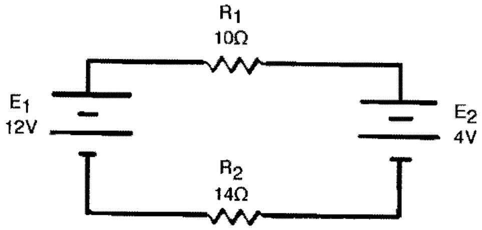
R1
10Ω
E1
12V
E2
4V
R2
14Ω

Figure 7-41
Circuit for Question 7.

8. Refer to the circuit shown in Figure 7-42A. Which of the following is the Thevenin equivalent of this circuit?

   A. Figure 7-42B.
   B. Figure 7-42C.
   C. Figure 7-42D.
   D. Figure 7-42E.

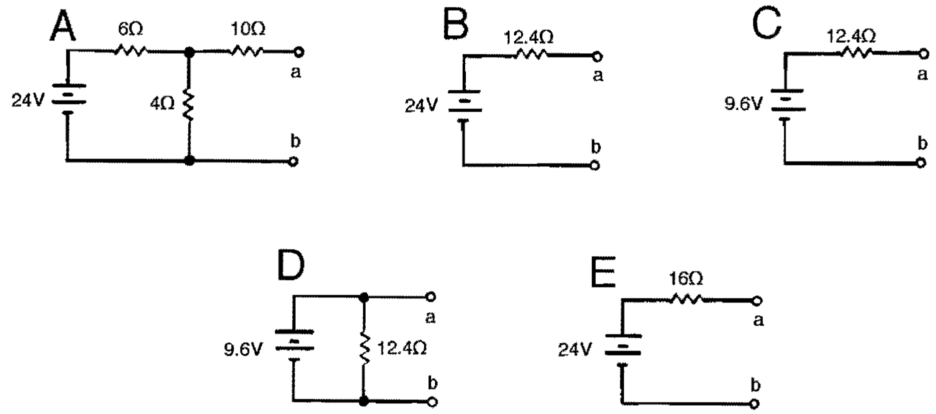
A
6Ω
10Ω
24V
4Ω
a
b
B
12.4Ω
24V
a
b
C
12.4Ω
9.6V
a
b
D
9.6V
12.4Ω
a
b
E
16Ω
24V
a
b

Figure 7-42
Circuit for Question 8.

9. Refer to the circuit shown in Figure 7-43A. Which of the following is the Norton equivalent of this circuit?

   A. Figure 7-43B.
   B. Figure 7-43C.
   C. Figure 7-43D.
   D. Figure 7-43E.

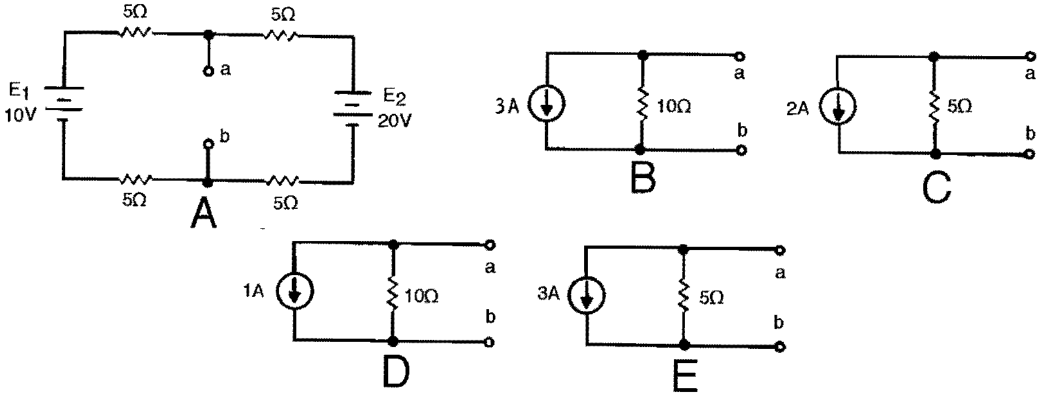
5Ω
5Ω
a
E_1
10V
E_2
20V
b
5Ω
5Ω
A
3A
10Ω
a
b
B
2A
5Ω
a
b
C
1A
10Ω
a
b
D
3A
5Ω
a
b
E

Figure 7-43
Circuits for Question 9.

10. Refer to Figure 7-44. Which two of the equivalent circuits shown represent the same circuit?

    A. A and D.
    B. C and B.
    C. A and E.
    D. E and F.

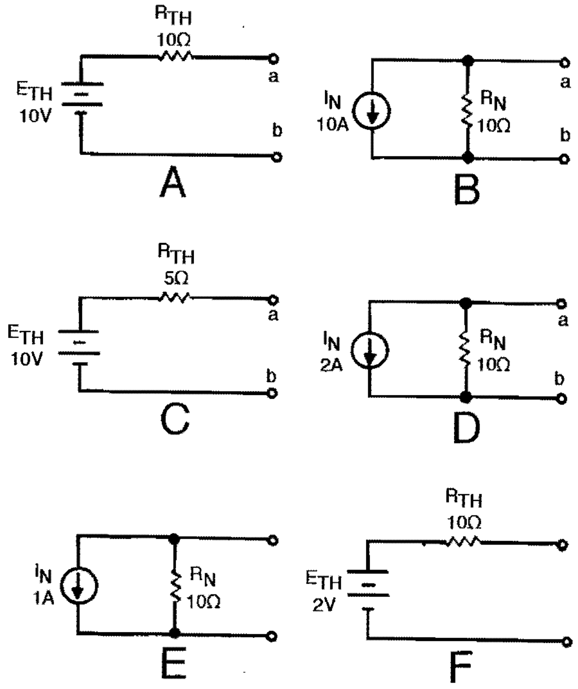
R_{TH}
10Ω
E_{TH}
10V
a
b
A
I_N
10A
R_N
10Ω
a
b
B
R_{TH}
5Ω
E_{TH}
10V
a
b
C
I_N
2A
R_N
10Ω
a
b
D
I_N
1A
R_N
10Ω
E
R_{TH}
10Ω
E_{TH}
2V
F

Figure 7-44
Circuits for Question 10.

11. Refer to the circuit shown in Figure 7-45. Use Thevenin's theorem to solve for the current through R_3. The current in R_3 is:

    A. 1 A.
    B. 2 A.
    C. 3 A.
    D. 4 A.

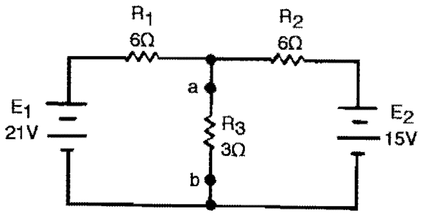
R_1
6Ω
R_2
6Ω
E_1
21V
a
R_3
3Ω
b
E_2
15V

Figure 7-45
Circuit for Question 11.

12. Refer to the circuit shown in Figure 7-46. Use Norton's theorem to solve for the current through R_3. The current in R_3 is:

    A. 3.0 A.
    B. 1.0 A.
    C. 1.5 A.
    D. 2.0 A.

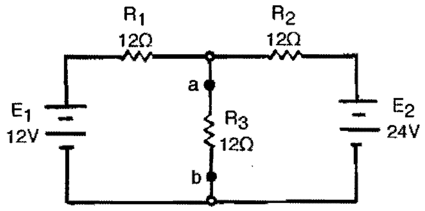

Figure 7-46
Circuit for Question 12.

13. In a voltage divider, the only current in the circuit that does not flow through one of the loads is called:

    A. non-load current.
    B. parallel current.
    C. bypass current.
    D. bleeder current.

14. The simplest form of voltage divider consists of a load and a resistor in series with the load. The resistor is called a:

    A. bleeder resistor.
    B. series dropping resistor.
    C. shunt resistor.
    D. thermistor.

15. A type of circuit that is designed to provide specific voltages and currents to varied loads is called a:

    A. Wheatstone bridge.
    B. norton's bridge.
    C. voltage divider.
    D. voltage coupler.

16. A circuit in which the current is directly proportional to the voltage is called a:

    A. linear circuit.
    B. balanced bridge network.
    C. series circuit.
    D. voltage divider.

17. A circuit that conducts equally well in either direction is called a:

    A. linear circuit.
    B. bilateral circuit.
    C. linear bridge.
    D. Wheatstone bridge.

18. Which of the following is not an application of the bridge circuit?

    A. Measuring resistance with the Wheatstone bridge.
    B. Controlling motion at a distance with a self-balancing bridge.
    C. A temperature-sensing circuit.
    D. A voltage doubler with the Wheatstone bridge.

EXAMINATION ANSWERS

1. A — R2 produces a voltage drop of 5 V and the total current through R_2 is 2 A. Consequently, the proper value of R_2 is:

$$R_2 = \frac{E}{I} = \frac{5\text{ V}}{2\text{ A}} = 2.5\ \Omega$$

2. D — R_3 drops 5 volts and its total current is 5 A. Thus:

$$R_3 = \frac{E}{I} = \frac{5\text{ V}}{5\text{ A}} = 1\ \Omega$$

3. B — The resistor must drop 8 volts when the current is 0.1 A. Therefore:

$$R = \frac{E}{I} = \frac{8\text{ V}}{0.1\text{ A}} = 80\ \Omega$$

4. B — The bridge shown in Figure 7-38B is the only one that does not satisfy the equation:

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

5. C — You must move the arm of R_2 up until the upper half of R_2 has the same resistance as the upper half of R_1.

6. D — Starting at point A, and working counterclockwise, you can write an equation for the loop through which I_1 flows:

$$E_1 - E_{R1} + E_2 - E_{R3} = 0$$

$$E_1 - R_1I_1 + E_2 - R_3(I_1 + I_2) = 0$$

$$20\text{ V} - 10\ \Omega\, I_1 + 15\text{ V} - 5\ \Omega\,(I_1 + I_2) = 0$$

$$20\text{ V} - 10\ \Omega\, I_1 + 15\text{ V} - 5\ \Omega\, I_1 - 5\ \Omega\, I_2 = 0$$

$$35\text{ V} - 15\ \Omega\, I_1 - 5\ \Omega\, I_2 = 0$$

$$-15\ \Omega\, I_1 - 5\ \Omega\, I_2 = -35\text{ V}$$

Starting at point B and working clockwise, you can write an equation for the loop through which I_2 flows:

$$E_3 + E_2 - E_{R3} - E_{R2} = 0$$

$$E_3 + E_2 - R_3(I_1 + I_2) - R_2(I_2) = 0$$

$$30\text{ V} + 15\text{ V} - 5\,\Omega(I_1 + I_2) - 10\,\Omega\, I_2 = 0$$

$$45\text{ V} - 5\,\Omega\, I_1 - 5\,\Omega\, I_2 - 10\,\Omega\, I_2 = 0$$

$$45\text{ V} - 5\,\Omega\, I_1 - 5\,\Omega\, I_2 = 0$$

$$-5\,\Omega\, I_1 - 15\,\Omega\, I_2 = -45\text{ V}$$

Thus our two loop equations are:

$$-15\,\Omega\, I_1 - 5\,\Omega\, I_2 = -35\text{ V}$$

$$-5\,\Omega\, I_1 - 15\,\Omega\, I_2 = -45\text{ V}$$

You can multiply the first equation times – 3 without upsetting the equality. Thus:

$$45\,\Omega\, I_1 + 15\,\Omega\, I_2 = 105\text{ V}$$

You can now add this to the second loop equation:

$$45\,\Omega\, I_1 + 15\,\Omega\, I_2 = 105\text{ V}$$

$$-5\,\Omega\, I_1 - 15\,\Omega\, I_2 = -45\text{ V}$$

$$40\,\Omega\, I_1 = 60\text{ V}$$

$$I_1 = 1.5\text{ A}$$

Now, substituting I_1 in either of the above equations, you can find I_2 =

$$-5\,\Omega\, I_1 - 15\,\Omega\, I_2 = -45\text{ V}$$

$$-5\,\Omega(1.5) - 15\,\Omega\, I_2 = -45\text{ V}$$

$$-7.5\text{ V} - 15\,\Omega\, I_2 = -45\text{ V}$$

$$-15\,\Omega\, I_2 = -37.5\text{ V}$$

$$I_2 = 2.5\text{ A}$$

The current through R_3 is the sum of I_1 and I_2. Thus:

$$I_{R3} = I_1 + I_2$$

$$I_{R3} = 1.5\text{ A} + 2.5\text{ A}$$

$$I_{R3} = 4\text{ A}$$

7. B — E_1 acts alone and attempts to force 0.5 amperes of current in a counterclockwise direction because:

$$I_1 = \frac{E_1}{R_T} = \frac{12\text{ V}}{24\ \Omega} = 0.5\text{ A}$$

E2 acts alone and attempts to force 0.1667 amperes of current in a clockwise direction because:

$$I_2 = \frac{E_2}{R_T} = \frac{4\text{ V}}{24\ \Omega} = 0.1667\text{ A}$$

Thus, the total current is:

$$I_T = I_1 - I_2$$

$$I_T = 0.5\text{ A} - 0.1667\text{ A}$$

$$I_T = 0.333\text{ A}$$

This causes a voltage drop across R_1:

$$E_{R1} = I_T \times R_1$$

$$E_{R1} = 0.333\text{ A} \times 10\ \Omega$$

$$E_{R1} = 3.33\text{ volts}$$

8. B — Remember E_{th} is the open circuit voltage or 9.6 V. R_{th} is the resistance between a and b when the battery is shorted. Thus, $R_{th} = 12.4\ \Omega$. E_{th} is in series with R_{th}. Thus, the circuit shown in Figure 7-45C is the Thevenin equivalent.

9. D — I_N is the current between a and b when these terminals are shorted. E_1 contributes 1 ampere while E_2 contributes 2 amperes. Thus, I_n is 3 amperes. R_N is the resistance measure between a and b when E_1 and E_2 are shorted. Therefore, R_N is 5 Ω. Consequently, the circuit shown in Figure 7-43E is the Norton equivalent.

10. C — If you apply Norton's theorem to the circuit shown in Figure 7-44A, the circuit shown in Figure 7-44E will result.

11. C — The first step is to apply Thevenin's theorem to find the Thevenin equivalent of all of the circuits except R_3. Thus, you break the circuit at points a and b as shown in Figure 7-47A. Now apply the superposition theorem to this circuit to find that the current is 0.5 A in the direction shown. This causes a 3-volt drop across each of the 6 Ω resistors. The open circuit voltage E_{th} is 18 V. When you short E_1 and E_2, you see that R_{th} is 3 Ω. Thus, the Thevenin equivalent is as shown in Figure 7-47B. If you now reconnect R_3 as shown in Figure 7-47C, you can solve for the current:

$$I = \frac{E_{th}}{R_{th} + R_3} = \frac{18\text{ V}}{6\,\Omega} = 3\text{ A}$$

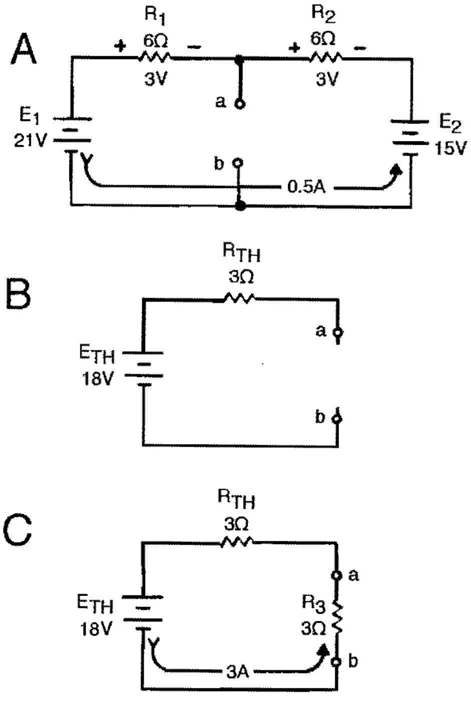

Figure 7-47

Solving Question 11.

12. B — First you must convert everything except R_3 to a Norton equivalent circuit. To find I_N, short points a and b as shown in Figure 7-48A. You find that I_N is 3 A. Next, you measure the open circuit resistance between a and b when E_1 and E_2 are shorted to find R_N. R_N is equal to 6 ohms. Thus, the Norton equivalent is shown in Figure 7-48B. Now if you reconnect R_3 across points a and b (Figure 7-48C) you find that the 3 A is distributed as shown. Notice that the current through R_3 is 1 A.

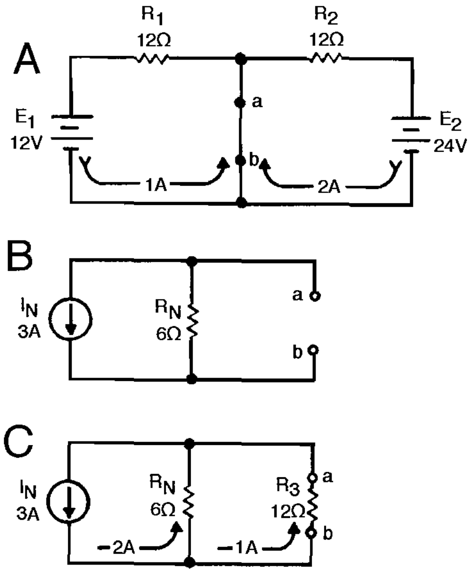

Figure 7-48
Solving Question 12.

13. D — In a voltage divider, the only current that does not flow through a load is bleeder current. Generally, bleeder current is about 10% of the total circuit current.

14. B — The most elementary form of a voltage divider consists of a dropping resistor in series with a load. This resistor drops voltage and limits current through the load.

15. C — A voltage divider is designed to provide specific currents and voltage to a varied group of loads.

16. A — In a linear circuit, the current is directly proportional to the voltage. If the voltage applied to the circuit doubles, the current through the circuit also doubles.

17. B — Bilateral circuits conduct equally well in either direction.

18. D — A bridge circuit cannot be used as a voltage doubler.

UNIT 8

INDUCTANCE AND CAPACITANCE

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INTRODUCTION

Inductors and capacitors are generally considered to be AC devices. However, they do have some important DC characteristics which you should know about. This unit serves as an introduction to these components.

UNIT OBJECTIVES

When you complete this unit, you will be able to:

1. Define the following terms: Induction, inductance, counter EMF, capacitance, RC time constant, RL time constant, farad, henry, self induction, steady-state condition, transient-state condition, and dielectric.
2. Identify the schematic symbols for the inductor and the capacitor.
3. State the three physical factors that determine capacitance.
4. Name two factors that increase the inductance of an inductor.
5. State how to determine the direction of an EMF that is induced into a conductor.
6. Given the values of resistance and inductance, determine the RL time constant for a circuit.
7. Given the values of resistance and capacitance, determine the RC time constant for a circuit.
8. Calculate total capacitance in series, parallel, and series-parallel.
9. Calculate total inductance in series, parallel, and series-parallel.

UNIT ACTIVITY GUIDE

	Completion Time
☐ Read “Inductance.”	________
☐ Complete Programmed Review Frames 1 through 16.	________
☐ Read “Capacitance.”	________
☐ Complete Programmed Review Frames 17 through 27.	________
☐ Read “Capacitors.”	________
☐ Complete Programmed Review Frames 28 through 41.	________
☐ Read “RC Time Constants.”	________
☐ Complete Programmed Review Frames 42 through 56.	________
☐ Perform Experiment 19.	________
☐ Read “Capacitors in Combination.”	________
☐ Complete Programmed Review Frames 57 through 62.	________
☐ Perform Experiment 20.	________
☐ Perform Experiment 21.	________
☐ Study Summary.	________
☐ Complete Unit Examination.	________
☐ Check Examination Answers.	________

INDUCTANCE

In an earlier unit on magnetism, you learned two rules that are also quite important when you study inductance. First, you saw that when current flows through a conductor, a magnetic field builds up around the conductor. Second, you saw that when a conductor is subjected to a moving magnetic field, a voltage is induced into the conductor. These two rules form the basis for a phenomenon called *self-induction.*

Self-Induction

Before you learn about self-induction, you must first differentiate between two different conditions which can exist in any DC circuit. The first is called the *steady-state condition* and the other is called the *transient condition.* Up to this point, you considered only the steady-state condition. In most DC circuits, this condition is reached within a fraction of a second after power is applied. In this condition, the current in the circuit has reached the value that you can compute with Ohm's Law. However, the current does not reach the steady-state value instantaneously. There is a brief period called the *transient time* in which the current builds up to its steady-state value. Thus, the transient condition exists for an instant after power is initially applied to a circuit. In circuits that contain only resistors, the transient condition exists for such a short period of time, that only sensitive instruments can detect it. However, if you use inductors or capacitors in the circuit, the transient condition may be extended so that it is readily apparent.

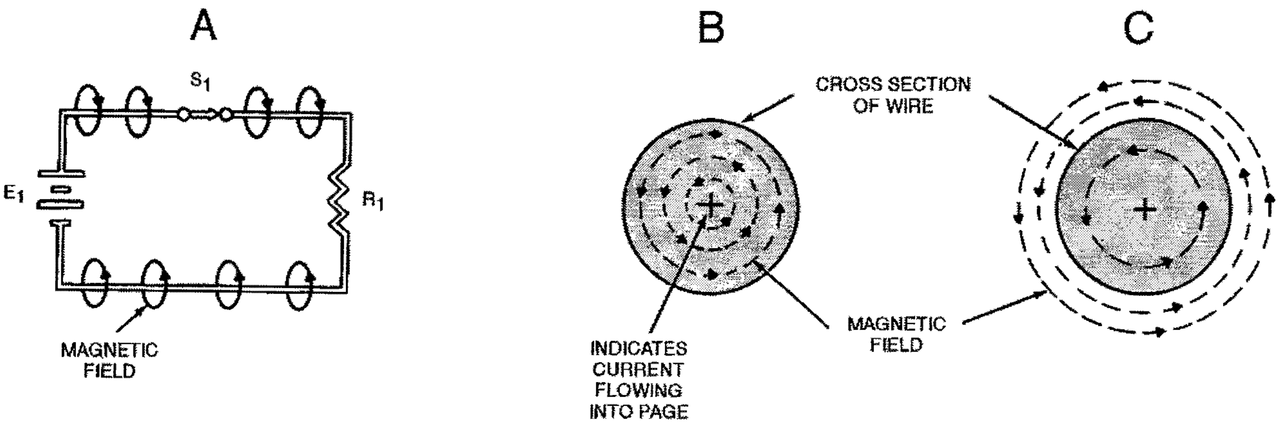


Figure 8-1
Self-induction.

During the transient time when the current changes from zero to some finite value, a phenomenon called self-induction occurs. Recall that a magnetic field builds up around any conductor when current flows. Also, when a conductor is cut by a moving magnetic field, a voltage is induced into the conductor. Keep these two facts in mind and consider what happens during the transient time in the DC circuit shown in Figure 8-1. When S_1 is closed, current begins to flow and a magnetic field builds up around the conductor as shown. However, the magnetic field does not just suddenly appear, it must buildup from the center of the wire. If you look at a cross section of the wire as shown in Figures 8-1B and C, you see that the magnetic field builds up over a period of time.

As the magnetic field expands from the center of the wire, it cuts the wire. This fulfills the requirements for inducing a voltage into the wire . Thus, the sequence of events is as follows:

1. the switch is closed
2. current begins to flow through the wire
3. a magnetic field begins to build up around the wire
4. the moving magnetic field induces a voltage into the wire

If you use the left-hand generator rule you learned about earlier, you can determine the polarity of the induced voltage and the direction of the induced current. Figure 8-2A shows the left-hand generator rule again to refresh your memory. Apply this rule to the cross section of the wire shown in Figure 8-1B. The tail of the arrow indicates that current flows into the page. Thus, the direction of the magnetic field is counterclockwise around the wire. Consequently, on the right side of the wire the general direction of the field is as shown in Figure 8-2B. Also, as the magnetic field expands outward on the right, the relative motion is the same as if the conductor had moved to the left. Apply the left-hand rule by pointing your thumb and forefinger as shown. Notice that your middle finger, which indicates the direction of the induced current, points out of the page. Thus, the induced current flows in the opposite direction to the original current.

Figure 8-2C shows that you will obtain the same result if you apply the left-hand rule to the field on the left side of the conductor. While it is true that the general direction of the field is reversed at this point, the relative motion of the conductor is also reversed so that the induced current still flows out of the page.

Figure 8-2D shows the relationship of the original current and the induced current. The original current induces a lower reverse current. The net result is that the original current is initially less than can you can account for with Ohm's Law.

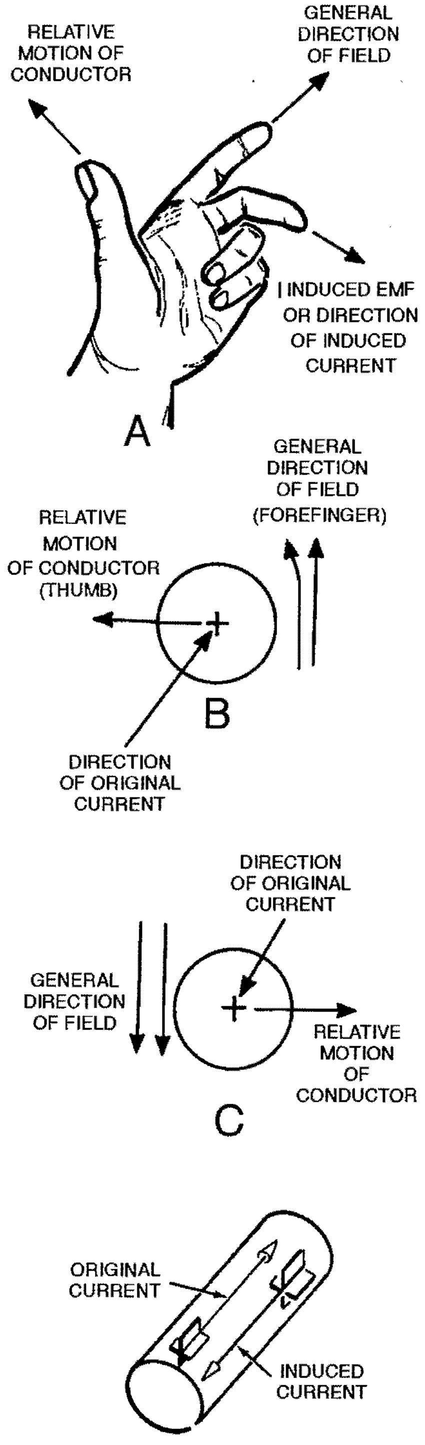

RELATIVE MOTION OF CONDUCTOR
GENERAL DIRECTION OF FIELD
INDUCED EMF OR DIRECTION OF INDUCED CURRENT
A
RELATIVE MOTION OF CONDUCTOR (THUMB)
GENERAL DIRECTION OF FIELD (FOREFINGER)
+
B
DIRECTION OF ORIGINAL CURRENT
DIRECTION OF ORIGINAL CURRENT
GENERAL DIRECTION OF FIELD
+
RELATIVE MOTION OF CONDUCTOR
C
ORIGINAL CURRENT
INDUCED CURRENT
D

Figure 8-2
Determining the direction of the induced current.

The induced current is caused by an induced EMF. The induced EMF attempts to force current counter to the original current. For this reason, the induced EMF is often called a *counter EMF*.

The counter EMF exists for the period of time while the magnetic field expands. Thus, it exists from the time that the switch is closed until the instant that the current reaches its steady state. In DC circuits, it exists only during the transient time. However, a transient condition also exists when you open the switch.

When the circuit is broken, the original current attempts to stop flowing. This causes the magnetic field to collapse. As the field collapses, it again induces an EMF into the conductor. With the left-hand rule, you can determine the direction of the resulting induced current. Refer to Figure 8-2B again. The general direction of the magnetic field remains the same. As the field collapses inward, the conductor is cut by the flux lines as they move to the left. Thus, the relative motion is the same as if the conductor were moving to the right. When you apply the left-hand rule, you find that the induced current is now in the same direction as the original current.

Of course, current cannot flow in an open circuit. Nevertheless, an EMF is induced which attempts to keep current flowing in the same direction. In some cases, the induced EMF is high enough to ionize the air between the switch contacts. In very high current circuits, the arc-over caused by the induced EMF can actually damage the switch contacts.

The process by which the induced EMF is produced is called *self-induction*. The effect of self-induction is opposition to changes in current flow. If the original current attempts to increase, self-induction opposes the increase. If the original current attempts to decrease, self-induction opposes the decrease. Self-induction may also be defined as the action of inducing an EMF into a conductor when there is a change of current in the conductor.

Inductance

Inductance is the ability of a device or circuit to oppose a change in current flow. Inductance may also be defined as the ability to induce an EMF when there is a change in current flow. Induction and inductance are easily confused, so you need to learn about the difference for a moment.

Induction is the action of inducing an EMF when there is a change in current. Obviously then, induction exists only when a change in current occurs. Inductance is different. It is the *ability* to cause an induced voltage for a change of current. If a circuit (or device) has this ability, it has it with or without current flow. Thus, inductance is a physical property. Like resistance, inductance exists whether current flows or not.

The unit of measurement for inductance is the henry (H). It was named in honor of Joseph Henry a nineteenth century physicist who did important research in this area of science. A henry is the amount of inductance which induces an EMF of 1 volt into a conductor when the current changes at the rate of 1 ampere per second. In most electronics applications, the henry is an inconveniently large quantity. For this reason, the quantities *millihenry* (mH) and *microhenry* (µH) are more commonly used.

The symbol for inductance is L. Thus, the statement "the inductance is 10 millihenrys" can be written as an equation:

$$L = 10\ \text{mH}$$

Inductors

As you saw, every conductor has a certain value of inductance. However, with short lengths of wire, the inductance value is so small that you can measure it only with very sensitive instruments. Many times in electronics, a specific amount of inductance is required in a circuit. A device which is designed to have a specific value of inductance is called an *inductor*.

Inductors come in various values from microhenries to several henries. The construction of the inductor is extremely simple. It consists of wire coiled around a core of some type. For this reason, the inductor is often called a coil.

Figure 8-3 shows why the inductance of a wire increases when it is wound into a coil. In Figure 8-3A a single loop is used. As the magnetic field expands or contracts, it cuts a single turn of wire and a small value of EMF is induced. Figure 8-3B shows what happens when two loops are wound together. Notice that the field is twice as strong and that both turns are cut by the entire field. Since both the field strength and the number of turns are doubled, the induced EMF increases by a factor of 4. Thus, the inductance is four times as high. Figure 8-3C shows three turns which produce a field strength three times as high as before. Now three times the number of flux lines cut three times the number of turns. Thus, the inductance and the induced EMF increase by a factor of 3 x 3 or 9. These examples show that the inductance of the coil varies as the number of turns squared.

Another way to dramatically increase the inductance is to wind the coil on a core material which has a high permeability. For example, a coil wound on a soft iron core has many times the inductance of an air-core coil.

Figure 8-3D shows the schematic symbol for the air-core coil or inductor. Figure 8-3E shows the symbol for the iron-core inductor. Although not indicated by the symbols, every inductor has a certain amount of resistance because the wire that is used to construct it has resistance.

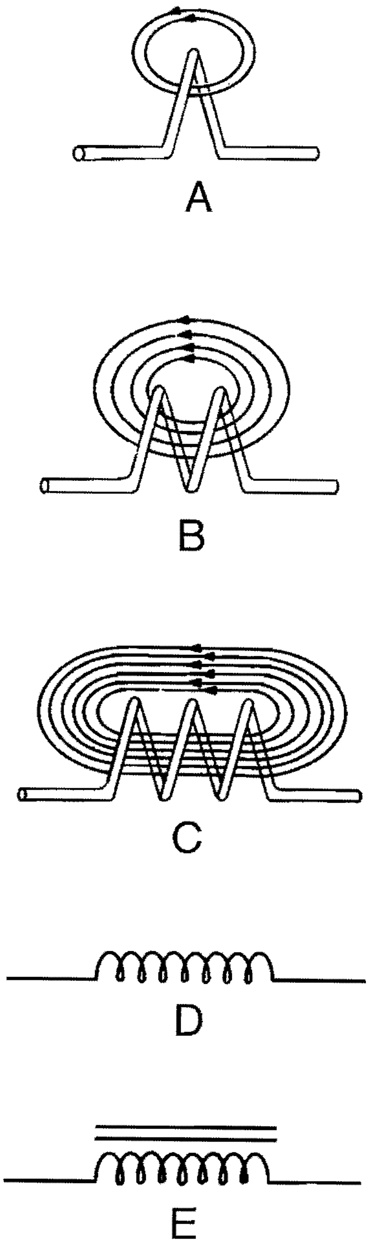


Figure 8-3
The inductor.

Time Constant of an Inductor

You saw that current cannot rise to its maximum value instantly when an inductance is in the circuit. The time required depends upon the value of the inductance and the value of any series resistance. For a given value of resistance, the time required for the current to build to its maximum value is directly proportional to the value of inductance. The higher the inductance, the more time is required for the current to reach maximum. On the other hand, for a given value of inductance, the time is inversely proportional to the resistance. The larger the resistance, the shorter the time required.

Mathematically, you can express this relationship with the equation:

$$t = L/R$$

In a circuit that consists of a 5 millihenry inductor and a 1 k ohm resistor, the time constant is:

$$t = \frac{.005}{1000} = .000005 \text{ second or } 5\ \mu\text{Sec}$$

For this circuit, 5 µSec is the length of time it takes for the current through the inductor to reach 63.2% of its maximum value. During each succeeding time constant, the current increases another 63.2% of the difference towards its maximum value. Look at the current through the example circuit after two time constants if the maximum current through the circuit is 100 amperes. The current after one time constant is:

$$100 \text{ amperes} \times .632 = 63.2 \text{ amperes}$$

and the current must increase another 36.8 amperes before it reaches maximum value.

During the second time constant, the current increases by 63.2% of the 36.8 amperes. The calculations look like this:

$$36.8 \text{ amperes} \times .632 = 23.25 \text{ amperes}$$

now:

$$63.2 \text{ amperes} + 23.25 \text{ amperes} = 86.45 \text{ amperes}$$

This is the current through the inductor after two time constants. After five time constants the current through the inductor is considered to be at its maximum value. Theoretically, the current through the circuit never reaches its maximum value.

Later, you will be introduced to time constant curves as a method of determining the percent of current or voltage after a given time constant.

Inductors in Combination

Inductors, like other components, can be connected in series, parallel, or series-parallel combinations. No matter what the combination, there are times when it is necessary to determine the total inductance of a circuit. This is how it is done.

Inductors in Series. When two inductors, each with 100 windings, are connected in series, they have the same overall effect on the circuit as one inductor with 200 windings. As the number of windings increases, the amount of inductance in the circuit increases. The inductance of the inductors is additive. That is, you can use this formula to determine the inductance of any number of inductors in series:

$$L_T = L_1 + L_2 + L_3$$

As you can see, inductors in series are treated the same as resistors in series. The total inductance is equal to the sum of the individual inductances.

Inductors in Parallel. A single inductor in a circuit has a given amount of inductance or opposition to a change in current flow. If you place another inductor of the same size in parallel with the first inductor, the amount of inductance in the circuit decreases. The reason for this is relatively simple. Each inductor still opposes the change in current through the circuit. However, because there are now two current paths, there is an overall decrease in opposition to current flow.

The formulas to determine inductance in parallel are essentially the same equations you use to determine resistance. They are:

$$L_T \frac{L_1 \times L_2}{L_2 + L_2}$$

or

$$L_T \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}}$$

or, for equal inductances in parallel:

$$L_T \frac{\text{Value of one inductor}}{\text{Number of inductors in parallel}}$$

Inductors in Series-Parallel. If a number of inductors are connected in a series-parallel circuit, you calculate the total inductance in the same way as the total resistance in a resistive circuit. First, you determine the inductance of any parallel portion when this is added to the inductance of any portion of the circuit in series with the parallel inductance. If you have any difficulty understanding this concept, refer back to the discussion of resistors in series-parallel given in Unit 3.

Programmed Review

1. Two conditions can exist in any DC circuit. The normal or ____________ condition exists after the current reaches its maximum or steady-state value.

2. (steady-state) Between the time that you close the switch and the time that the current reaches maximum is called the ____________ time.

3. (transient) During this time, the current increases and a ____________ ____________ builds up around the conductors.

4. (magnetic field) The field cuts the conductor and induces an EMF. The induced EMF tries to push current through the conductor in the ____________ direction.
same/opposite

5. (opposite) Since the induced current attempts to flow counter to the original current, the induced EMF is sometimes called a ____________ EMF.

6. (counter) When you reopen the switch, the magnetic field collapses and induces an EMF which ____________ the original current.
aids/opposes

7. (aids) In both cases, the induced EMF tends to oppose any ____________ in current.

8. (change) The action of inducing an EMF when there is a change in current is called ____________ .

9. (induction) The ability or physical characteristics of a conductor or coil to oppose a change in current is called ____________ .

10. (inductance) The unit of measurement for inductance is the ________ .

11. (henry) One henry is the value of inductance which induces an EMF of one ____________ when the current changes at the rate of one ampere per second.

12. (volt) A device designed to have a specific inductance is called an ____________ .

13. (inductor) The length of time that is required for the current in a circuit to reach its maximum value is determined by both the ____________ and the ____________ .

14. (inductance, resistance) The length of time increases if the ____________ increases.

15. (inductance) The length of time increases if the resistance __________ .

16. (decreases)

CAPACITANCE

Capacitance is the property of a circuit or device which enables it to store electrical energy by means of an *electrostatic* field. A device that is especially designed to have a certain value of capacitance is called a *capacitor.* The capacitor has the ability to store electrons and release them at a later time. The number of electrons that it can store for a given applied voltage is a measure of its *capacitance.*

Capacitors

In the early days of electronics, the word condenser was used instead of capacitor. However, today the word condenser is rarely used except in special cases. An automobile mechanic may still call the capacitor in an ignition system a condenser but the more correct term is capacitor.

Figure 8-4 shows the principle parts of a capacitor. It consists of two metal plates separated by a non-conducting material called a *dielectric.* Often metal foil is used for the plates while the dielectric may be paper, glass, ceramic, mica, or some other type of good insulator.

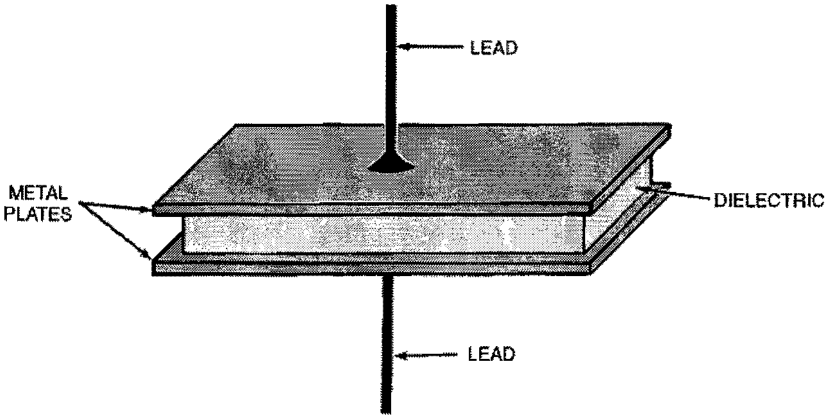


Figure 8-4
The capacitor.

The actual construction of the capacitor may look quite different from that shown in Figure 8-4. For example, Figure 8-5 shows how the paper dielectric capacitor is made. Two thin sheets of metal foil are separated by a sheet of paper. Additional sheets of paper are placed on the top and bottom of the foil sheets. The sheets are then wound into a compact cylinder. Leads are attached to each of the foil sheets. Finally, a wax or plastic case is added to seal the entire unit into a permanent package.

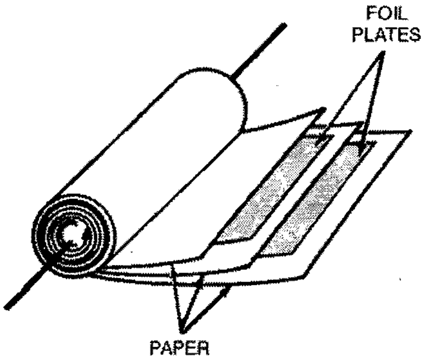


Figure 8-5

Construction of the paper capacitor.

Charging the Capacitor

The most useful characteristic of the capacitor is its ability to store an electrical charge. Figure 8-6 illustrates the charging action. For simplicity, the capacitor is shown as two metal plates. In Figure 8-6A the capacitor is not charged. This means that there are the same number of free electrons in both plates. Naturally then, there is no difference of potential between the two plates and if you connect a voltmeter across the plates, it would read 0 volts. No current flows in the circuit because switch S_1 is open.

Figure 8-6B shows what happens when you close S_1. With S_1 closed, the positive terminal of the battery connects to the upper plate of the capacitor. The positive charge of the battery attracts the free electrons in the upper plate. Thus, these electrons flow out of the upper plate to the positive terminal of the battery. At the same instant, the positive upper plate of the capacitor attracts the free electrons in the negative plate. However, because the two plates are separated by an insulator, no electrons can flow to the upper plate from the lower plate. Nevertheless, the attraction of the positive charge on the upper plate pulls free electrons into the lower plate. Thus, for every electron that leaves the upper plate and flows to the positive terminal of the battery, another electron leaves the negative terminal and flows into the bottom plate.

As the capacitor charges, a difference of potential begins to build up across the two plates. Also, an electric field is established in the dielectric material between the plates. The capacitor continues to charge until the difference of potential between the two plates is the same as the voltage across the battery. In the example shown, current flows until the charge on the capacitor builds up to 10 volts. Once the capacitor has the same EMF as the battery, no additional current can flow because there is no longer a difference of potential between the battery and the capacitor.

Note again that although current flows in the circuit while the capacitor charges, current does not flow through the capacitor. Electrons flow out of the positive plate and into the negative plate. However, the insulating dielectric prevents electrons flow through the capacitor. Moreover, if electrons do flow through the dielectric, the capacitor would not develop a charge in the first place. It would simply produce a voltage drop in the same way as a resistor.

Figure 8-6C shows that once the capacitor has been charged, you can open the switch and the capacitor retains its charge. A good capacitor can retain a charge for a long period of time.

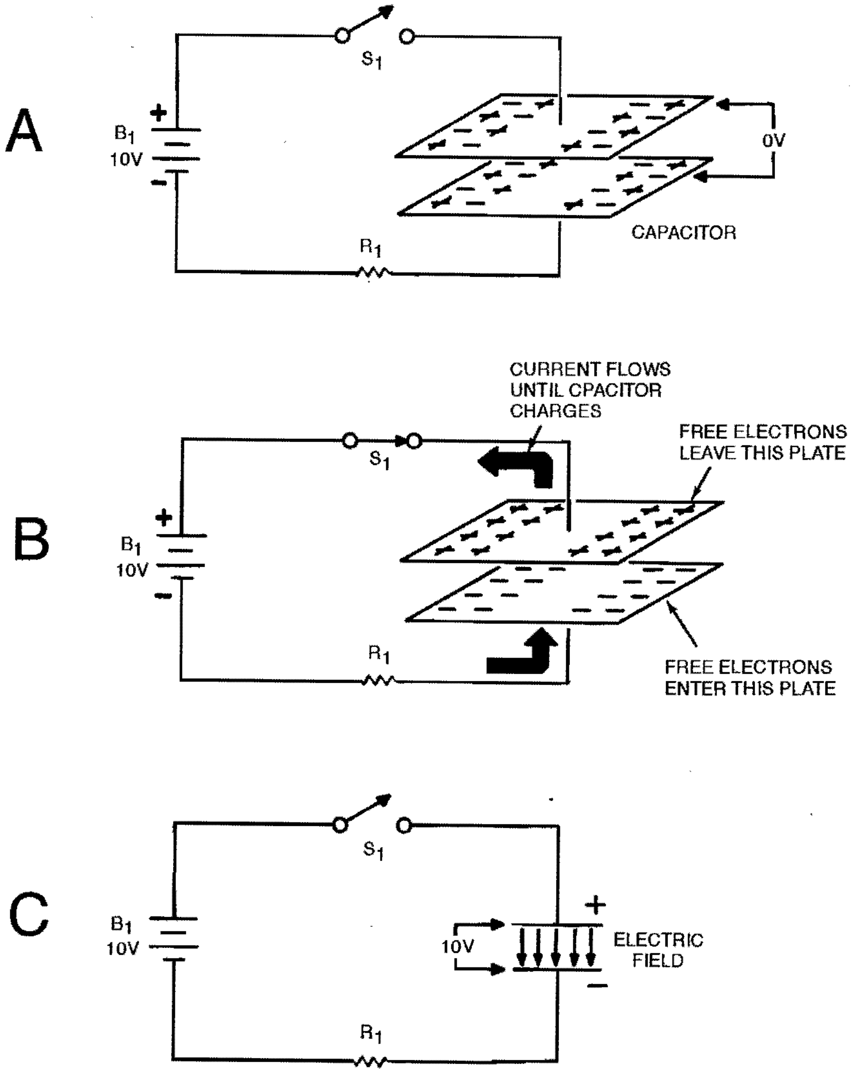

A
S1
B1
10V
+
-
0V
CAPACITOR
R1
B
CURRENT FLOWS
UNTIL CPACITOR
CHARGES
FREE ELECTRONS
LEAVE THIS PLATE
S1
B1
10V
+
-
R1
FREE ELECTRONS
ENTER THIS PLATE
C
S1
B1
10V
10V
+
-
ELECTRIC
FIELD
R1

Figure 8-6

Charging the capacitor.

Discharging the Capacitor

Theoretically, you can recover all of the energy that is stored in a capacitor. Thus, a perfect capacitor dissipates no power. It would simply store energy and later release the energy. While it is impossible to build a perfect capacitor, you can approach this condition. The act of storing the energy is called *charging* the capacitor. The act of recovering the energy is called *discharging* the capacitor.

Figure 8-7 illustrates the charge and discharge cycle. In Figure 8-7A, the arm of S_1 connects the capacitor C_1 placed directly across the battery. Notice the schematic symbol that represents the capacitor. A current flows as shown and charges the capacitor to 10 volts.

Once the capacitor is charged, move the arm of S_1 to its other position as shown in Figure 8-7B. This removes C_1 from across the battery and places C_1 across R_2 instead. The free electrons on the negative plate now rush through R_2 to the positively charged plate. Electron flow continues until the two plates again reach the same potential. At this time, you can consider the capacitor to be discharged and the current flow in the circuit stops.

As the capacitor discharges, the voltage across it decreases. When it is completely discharged, the voltage across the capacitor is once again 0 volts. At this time, all the energy which was initially stored has been released. The power that is consumed by R_2 is provided by the battery, and C_1 is a temporary storage medium.

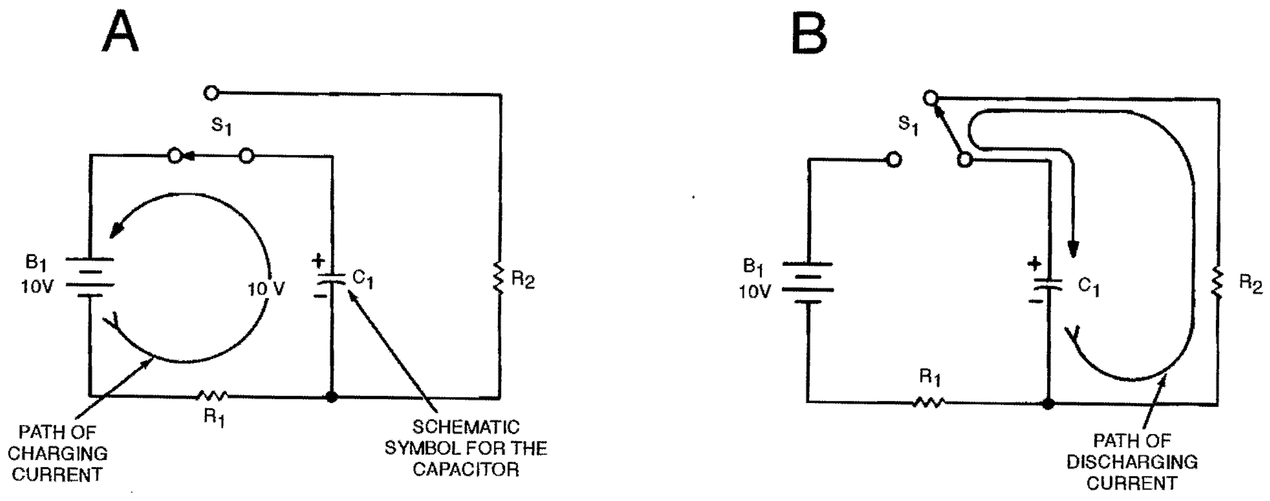

A
S1
B1
10V
10 V
+
C1
R2
R1
PATH OF CHARGING CURRENT
SCHEMATIC SYMBOL FOR THE CAPACITOR
B
S1
B1
10V
+
C1
R2
R1
PATH OF DISCHARGING CURRENT

Figure 8-7
Discharging the capacitor.

Programmed Review

17. That property of a circuit or device which enables it to store energy by means of an electric field is called ____________ .

18. (capacitance) A device that is designed to have a certain value of capacitance is called a ____________ .

19. (capacitor) A capacitor consists of two ____________ ____________ separated by an insulator.

20. (metal plates) The insulator is called a ____________ .

21. (dielectric) When a battery is connected across a capacitor, electrons flow from one plate of the capacitor to the ____________ terminal of the battery.

22. (positive) At the same time, electrons flow from the ____________ terminal of the battery to the other capacitor plate.

23. (negative) Current flows in the circuit until the capacitor becomes completely ____________ .

24. (charged) When a capacitor is completely charged, the voltage across it is equal to the voltage across the ____________ .

25. (battery) If a capacitor is disconnected from a battery and then connected across a resistor, it will ____________ through the resistor.

26. (discharge) The discharge continues until the EMF across the capacitor is ____________ volts.

27. (0)

CAPACITORS

In many types of electronic equipment, a capacitor is used more often than any other type of component except the resistor. Thus, it is important that you learn as much as possible about these devices.

Unit of Capacitance

Capacitance is a measure of the amount of charge that a capacitor can store for a given applied voltage. The unit of capacitance is the *farad* (F). It was named in honor of Michael Faraday. One farad is the amount of capacitance that will store a charge of one coulomb when an EMF of one volt is applied. One farad is an extremely large value of capacitance. For this reason, the unit microfarad (µF) meaning one millionth of a farad is used more often. Even the microfarad is frequently too large. In these cases, the unit micro-microfarad (µµF) is used. The more modern name for the micro-microfarad is the picofarad (pF).

To summarize, the farad is the amount of capacitance that will store one coulomb of charge when one volt is applied. The microfarad is one millionth of a farad. The picofarad is one millionth of a microfarad or

$$\frac{1}{1{,}000{,}000{,}000{,}000}$$

of a farad. In powers of ten, the microfarad is 10^{-6} farad while the picofarad is 10^{-12} farad.

This formula expresses capacitance in terms of charge and voltage:

$$C = \frac{Q}{E}$$

C is the capacitance in farads; Q is the charge in coulombs; and E is the EMF in volts.

Factors Determining Capacitance

Capacitance is determined by three factors:

1. the area of the metal plates,
2. the spacing between the plates, and
3. the nature of the dielectric.

This is illustrated in Figure 8-8. Figure 8-8A shows a capacitor that is made up of two 1-inch square plates which are separated by 0.001 inch. The dielectric is air. Such a device has a capacitance of 225 pF. You will use this capacitor as a reference to see what happens when you change the area of the plates, the spacing of the plates, and the nature of the dielectric.

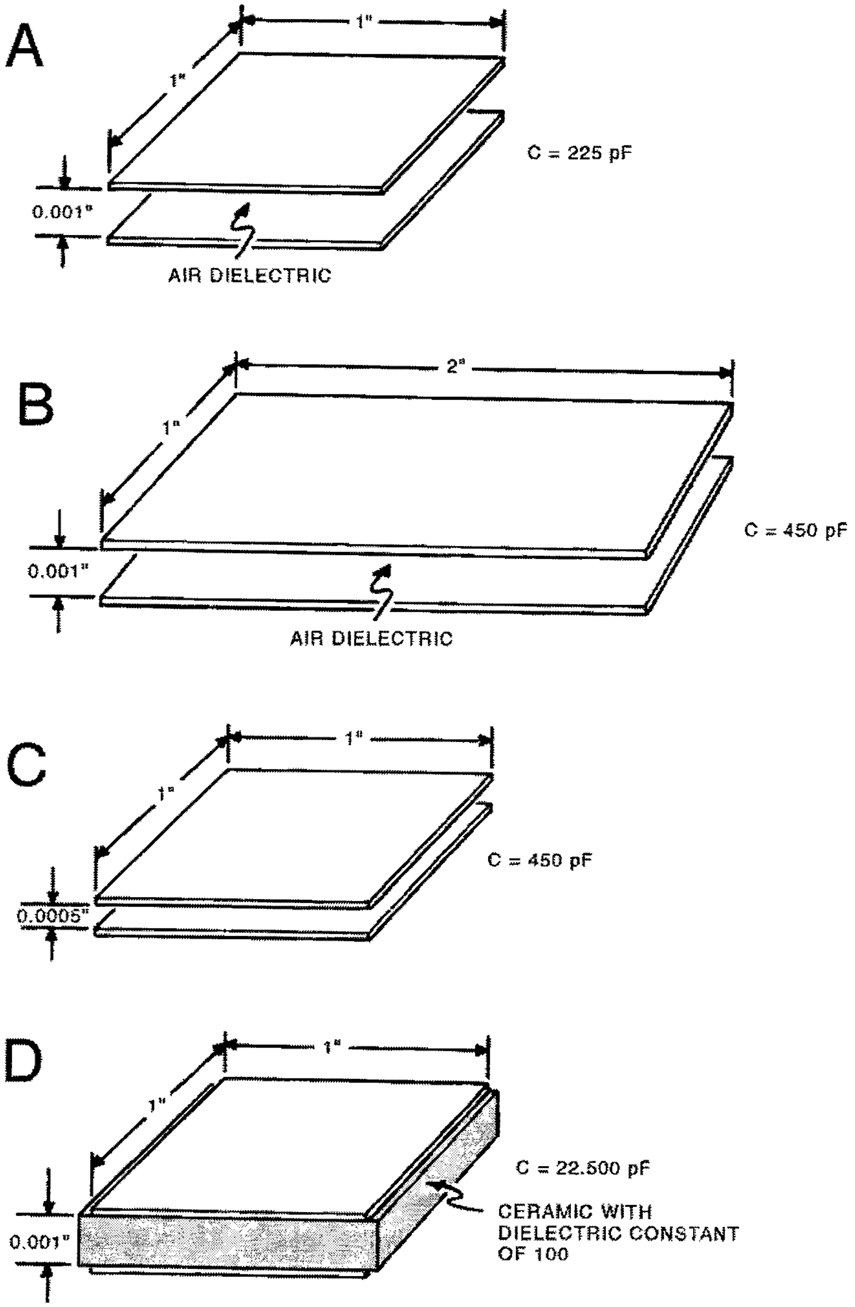

A
1"
1"
C = 225 pF
0.001"
AIR DIELECTRIC
B
2"
1"
C = 450 pF
0.001"
AIR DIELECTRIC
C
1"
1"
C = 450 pF
0.0005"
D
1"
1"
C = 22.500 pF
CERAMIC WITH
DIELECTRIC CONSTANT
OF 100
0.001"

Figure 8-8
Factors which determine capacitance.

Figure 8-8B shows what happens when you double the area of the plates but hold all other factors constant. Notice that there is now twice as much area in which the electrostatic field can exist. This doubles the capacity or capacitance of the device. The capacitance value doubles to 450 pF. Thus, capacitance is directly proportional to the area of the plates.

Figure 8-8C shows that you can also reduce the spacing between the plates to one half its former value to double the capacitance. The path of the electrostatic lines of force is cut in half. This doubles the strength of the field which, in turn, doubles the capacitance. Thus, capacitance is inversely proportional to the spacing between the plates.

Finally, Figure 8-8D shows that you can use a better dielectric than air to greatly increase the capacitance. Air makes a very poor dielectric. Most insulators support electrostatic lines of force more easily than air. The ease with which an insulator supports electrostatic lines of force is indicated by its *dielectric constant.* Air is used as a reference. It is arbitrarily given a dielectric constant of 1. Most insulators have a higher dielectric constant. For example, a sheet of waxed paper has a dielectric constant of about 3. This means that a sheet of 0.001 inch waxed paper that is placed between the plates would triple the capacitance.

Some typical dielectric constants for common types of insulators are shown in Figure 8-9:

Material	Dielectric Constant (K)
Air	1
Vacuum	1
Waxed Paper	3 – 4
Mica	5 – 7
Glass	4 – 10
Rubber	2 – 3
Ceramics	10 – 5000

Figure 8-9
Dielectric constants of some types of insulators.

Figure 8-8D shows that when you insert an insulator that has a dielectric constant of 100 between the plates, the capacitance value increases by a factor of 100. Thus, capacitance is directly proportional to the dielectric constant.

This formula combines the three factors described above:

$$C = 0.225\, K \frac{A}{d}$$

C is the capacitance in picofarads; K is the dielectric constant; A is the area (in square inches) of one plate; and d is the distance (in inches) between the two plates.

Types of Capacitors

Capacitors are available in many different shapes and sizes. However, all capacitors are in one of two categories: variable and fixed. The next few paragraphs describe these two categories in more detail.

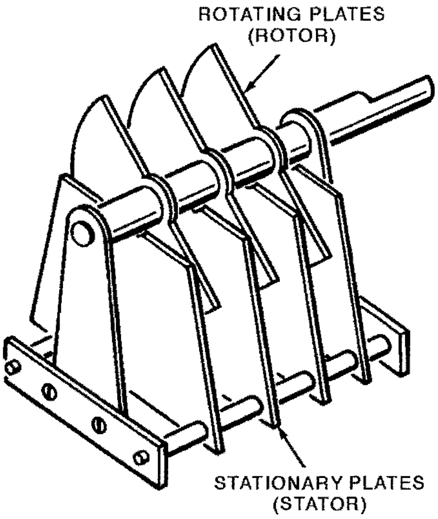


Figure 8-10
The variable capacitor.

Variable Capacitors. Figure 8-10 shows the construction of an air dielectric variable capacitor. The capacitance value of this type of capacitor changes when you rotate the shaft. The rotating plates are attached to the shaft. As the shaft turns, the rotating plates change position in relation to the stationary plates. The rotating plates are electrically connected and form one plate of the capacitor. The stationary plates are also electrically connected. They form the other plate of the capacitor. The rotating plates and stationary plates mesh together but do not touch. When you move the shaft, the area of the plates across from each other changes from maximum when they are fully meshed (closed) to minimum when they are fully open. As you saw, this changes the capacitance of the device.

Fixed Capacitors. Most fixed capacitors are constructed as shown earlier in Figure 8-5. They consist of alternate layers of metal foil (plates) and insulators (dielectric). Capacitors are often named for their dielectric.

Capacitors are often named for their dielectric. Thus, there are paper, ceramic, and mica capacitors. Also, capacitors are sometimes classified according to their shape. Thus, there are disc capacitors, tubular capacitors, and chip capacitors.

One of the most popular types of fixed capacitor is the electrolytic capacitor. Its construction is illustrated in Figure 8-11. Sheets of metal foil are separated by a sheet of paper or gauze which has been saturated with a chemical paste called an electrolyte. The electrolyte is a good conductor and, therefore, the paper is not the dielectric. Actually, the dielectric is formed during the manufacturing process. A DC voltage is applied across the foil plates. As current flows, a thin layer of aluminum oxide builds up on the plate which is connected to the positive side of the DC voltage. As shown in Figure 8-11C, the oxide layer is extremely thin. Because the oxide is a fairly good insulator, it acts like a dielectric. The upper foil becomes the positive plate; the oxide becomes the dielectric; and the electrolyte becomes the negative plate. Note that the bottom layer of foil simply provides a connection to the electrolyte.

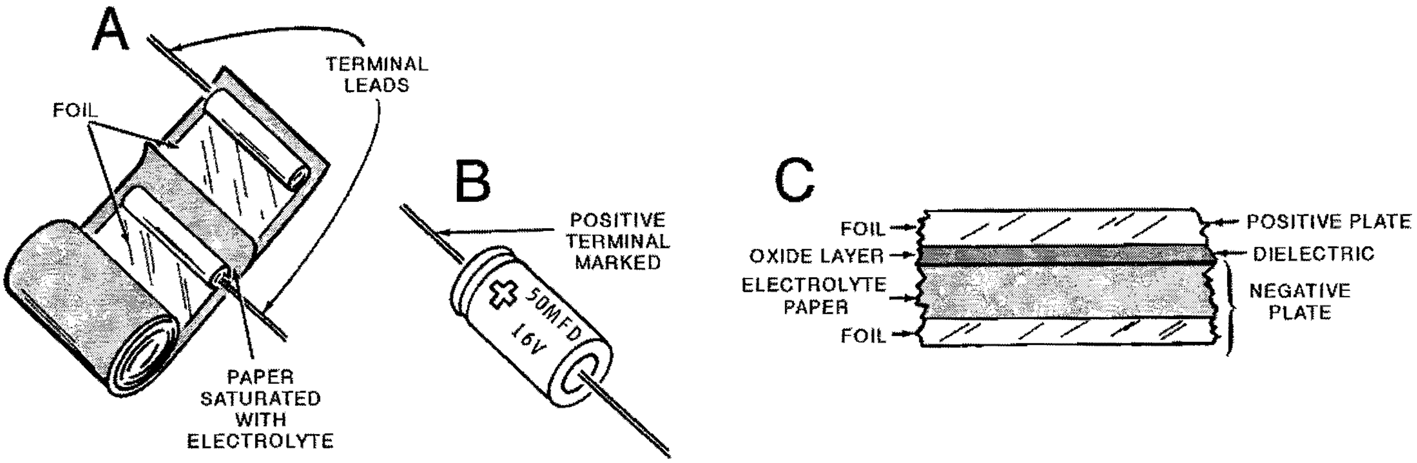


Figure 8-11
The electrolytic capacitor.

Recall that capacitance is inversely proportional to the spacing between plates. Because the oxide layer is extremely thin, very high values of capacitance are possible with this technique. While most other capacitors have values below 1 μF, an electrolytic capacitor may have values that range from about 1 μF up to thousands of microfarads.

Because of its construction, the electrolytic capacitor is *polarized.* This means that the capacitor has a negative and a positive lead. When it is connected in a circuit, you must connect the positive lead to the more positive point. The positive lead is marked on the capacitor shown in Figure 8-11. However, many capacitors have only the negative lead marked.

An important characteristic of the electrolytic (or any other type of capacitor) is its voltage rating. The voltage rating indicates the maximum voltage that the capacitor can withstand without the dielectric breaking down or arcing over. With electrolytic capacitors this value is generally printed on the capacitor along with its capacitance value.

Like resistors, there is a another type of capacitor called a chip capacitor. It too does not have leads. Instead, it has metal contacts on the ends that allow you to solder it directly to circuit board foils. Figure 8-12 shows an internal view of a chip capacitor.

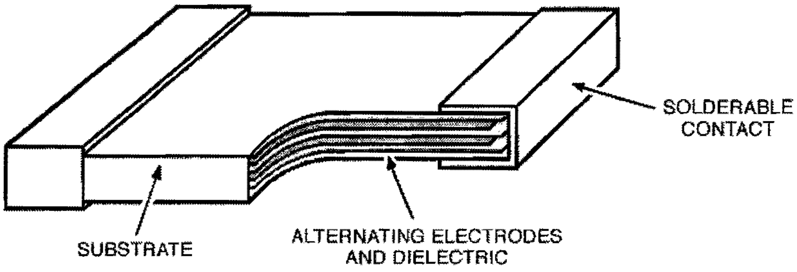


Figure 8-12
Internal view of a chip capacitor.

Ceramic chip capacitors consist of alternating layers of ceramic and thin films of metal. These alternating layers are built up one-by-one with thin layers of liquid ceramic or dry ceramic tape. Conductive electrodes are screen printed over each ceramic layer before the next layer is added. If liquid ceramic is used during manufacture, it is allowed to dry before the electrode film is applied. The completed stack is then cut into individual chips.

The alternating electrode layers within the chip are connected together when the solderable contacts are applied to each end of the individual chips. As you can see in the Figure, the finished capacitor is completely sealed inside a protective ceramic and metal coating.

The number of electrode layers and the dimensions of the capacitor are two factors which determine the capacitance of a chip capacitor. Another factor which affects the capacitance of a chip capacitor is the ceramic that separates the metal layers. The ceramic within a chip capacitor forms the capacitor's structural material as well as its dielectric. Higher values of capacitance have more alternating layers and are larger. Chip capacitors range from about 0.5 pF to 1.0 μF.

Chip capacitor sizes range from 0.080" to 0.225" long × 0.050" to 0.175" wide × 0.050" to 0.070" thick.

Programmed Review

28. The unit of capacitance is the ___________ .

29. (farad) One farad is the amount of capacitance that will store a charge of one ___________ when an EMF of one ___________ is applied.

30. (coulomb, volt) Because the farad is so large, the units ___________ (meaning millionth of a farad) and ___________ (meaning millionth of a millionth of a farad) are used.

31. (microfarad, picofarad) A formula which expresses capacitance in terms of charge and EMF is C = ___________ .

32. ($C = \frac{Q}{E}$) One of the factors which determines capacitance is the ___________ of the two plates of the capacitor.

33. (area) The larger the area, the ___________ the value of the capacitor.
higher/lower

34. (higher) Another factor is the ___________ between the plates of the capacitor.

35. (distance or spacing) The greater the distance between the plates, the ___________ the value of capacitance.
higher/lower

36. (lower) The third factor that determines capacitance is the nature of the ___________ .

37. (dielectric) The higher the dielectric constant, the ___________ the capacitance will be.
higher/lower

38. (higher) One form of variable capacitor employs rotary plates which are meshed with stationary plates. This type of capacitor uses ____________ as a dielectric.

39. (air) A popular type of fixed capacitor is the electrolytic. In the electrolytic capacitor, the ____________ is a very thin layer of aluminum oxide.

40. (dielectric) Because of its unique construction, the electrolytic capacitor is ____________. This means that you must always connect its positive plate to a more positive voltage than its negative plate.

41. (polarized) The prime advantage of the electrolytic is that a very large value of capacitance can be packed in a small package.

RC TIME CONSTANTS

When you connect a capacitor across a DC voltage source, it charges to the applied voltage. If you then connect the charged capacitor across a load, it will discharge through the load. You can compute the length of time that is required for a capacitor to charge or discharge if you know certain circuit values.

There are only two factors which determine the charge or discharge time. These are the value of the capacitor and the value of the resistance through which the capacitor must charge or discharge. The time is directly proportional to both resistance and capacitance. To understand the relationship between resistance, capacitance, and time, you must consider the idea of an *RC time constant.*

The time constant is the time that is required for a capacitor to charge to 63.2 percent of the applied voltage. Or, if the capacitor is being discharged, the time constant is the length of time that is required for the voltage across the capacitor to drop by 63.2 percent.

You can use the following equation to express the time constant:

$$t = R \times C$$

Here, t is the time constant in seconds (time that is required to reach 63.2 percent of full charge); R is the resistance in ohms; and C is the capacitance in farads. As you learned earlier, the farad is too large to be practical and capacitance is most often expressed in microfarads. In the above equation, if C is in microfarads and R is in ohms, then t is in microseconds. If C is in microfarads and R is in kilohms, then t is in milliseconds. Finally, if C is in microfarads and R is in megohms, then t is in seconds.

Some examples may help illustrate this.

If $C = 1\ \mu F$ and $R = 100\ \Omega$:

$t = R \times C$
$t = 100\ \Omega \times 1\ \mu F$
$t =$ 100 microseconds

If $C = 1\ \mu F$ and $R = 10\ k\Omega$:

$t = R \times C$
$t = 10\ k\Omega \times 1\ \mu F$
$t =$ 10 milliseconds

If $C = 1\ \mu F$ and $R = 2\ M\Omega$:

$t = R \times C$
$t = 2\ M\Omega \times 1\ \mu F$
$t =$ 2 seconds

As you study these examples, keep in mind that the time constant (t) is *not* the time that is required to fully charge (or discharge) the capacitor. Rather, it is the time that is required to charge the capacitor to 63.2 percent of the applied voltage. To see how a capacitor charges, consider a specific example. Figure 8-13 shows a 1 μF capacitor that is connected in series with a 1 MΩ resistor. Thus, the time constant is 1 second. Initially, the capacitor is completely discharged and the voltage across it is 0 volts. Note how the capacitor charges when you move the arm of the switch up so that the 100-volt power supply is connected to the R-C network.

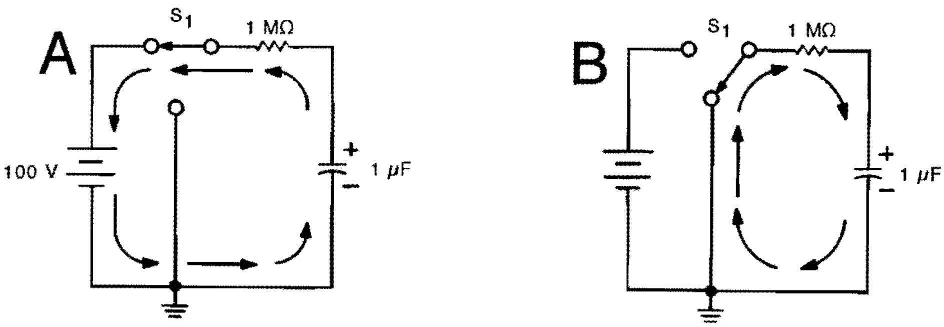


Figure 8-13
Working with time constants.

When the capacitor is connected across the voltage source, it attempts to charge to the level of the applied voltage. However, the capacitor does not charge instantaneously. The time constant of the circuit is:

$$t = R \times C$$
$$t = 1\ \text{M}\Omega \times 1\ \mu\text{F}$$
$$t = 1\ \text{second}$$

Thus, after 1 second (1 time constant), the capacitor charges to 63.2 percent of the applied voltage or to 63.2 volts.

Figure 8-14 shows two curves which are helpful when you work with time constants. Curve A shows how a capacitor charges. Initially, the capacitor charges rapidly, charging to 63.2 percent of the applied voltage during the first time constant. However, as time passes, the capacitor begins to charge more slowly.

During the second time constant, the capacitor charges to 63.2 percent of the remaining voltage. In our example, the remaining voltage after 1 time constant (1 second) is 100 V − 63.2 V = 36.8 V. Now, 63.2 percent of 36.8 V is about 23.3 V. Thus, at the end of the second time constant (after 2 seconds) the voltage on the capacitor has risen to: 63.2 V + 23.3 V = 86.5 V. This is 86.5 percent of the applied voltage.

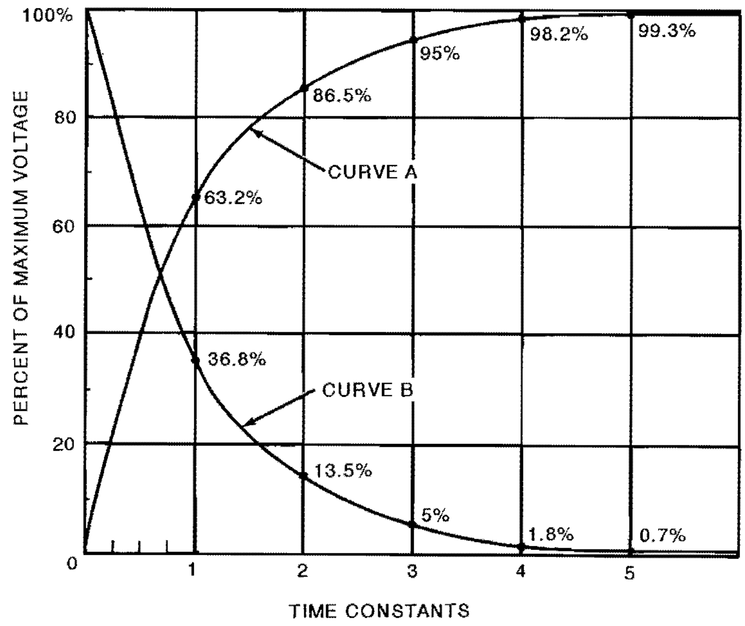


Figure 8-14
Time constant curves.

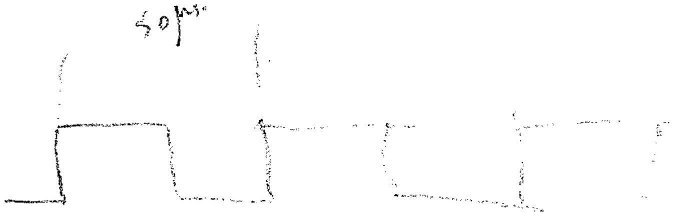
During the third time constant, the capacitor once again charges to 63.2 percent of the remaining voltage. After 3 time constants (3 seconds), the capacitor has charged to 95 percent. After 4 time constants (4 seconds), it has charged to 98.2 percent; and after 5 time constants to more than 99 percent. For most purposes, you can consider the capacitor to be fully charged after five time constants. (You may recognize this mathematical progression from the previous discussion of inductors. The percentages on the curves shown in Figure 8-13 are the same as with inductors. Therefore, you can apply this Figure to current calculations with inductors.)

Because of its shape, curve A is called an exponential curve. The capacitor charges exponentially.

Curve B of Figure 8-14 shows how the capacitor discharges. At the first instant, the capacitor is fully charged. During the first time constant, the voltage drops by 63.2 percent to 36.8 percent of its original value. During the second time constant, the voltage drops an additional 63.2 percent or to only 13.5 percent of its original value. The voltage drops to about 5 percent at three time constants and to only 1.8 percent after four. After five time constants, the charge is less than 1 percent of its original value. For most practical purposes, you can consider the capacitor to be fully discharged after five time constants.

In Figure 8-13A, the capacitor charges to approximately 100 volts in 5 seconds. Figure 8-13B shows the capacitor being discharged. According to curve B, the charge on the capacitor is:

100 volts initially;
36.8 volts after 1 time constant (1 second);
13.5 volts after 2 time constants (2 seconds);
5 volts after 3 time constants (3 seconds);
1.8 volts after 4 time constants (4 seconds);
and 0.7 volts after 5 time constants (5 seconds).



Programmed Review

42. The time that is required for a capacitor to charge or discharge is determined by the value of the __________ and the value of any __________ through which it must discharge.

43. (capacitance, resistance) The capacitor does not charge in a linear manner. It charges to 63.2 percent of the applied voltage in a relatively short time. This time is referred to as a time __________ .

44. (constant) To compute the time constant, you multiply the value of the capacitor by the value of the resistance. Thus the formula for the time constant is t = __________ .

45. (t = R x C) If R is in megohms and C is in microfarads, t is in __________ .

46. (seconds) On the other hand, if R is in kilohms and C is in microfarads, t is in __________ .

47. (milliseconds) Finally, if R is in ohms and C is in microfarads, t is in __________ .

48. (microseconds) Refer to Figure 8-15A. With the switch in the position shown, C_1 starts charging toward the applied voltage. The RC time constant is 200 kΩ x 1 µF = __________ .

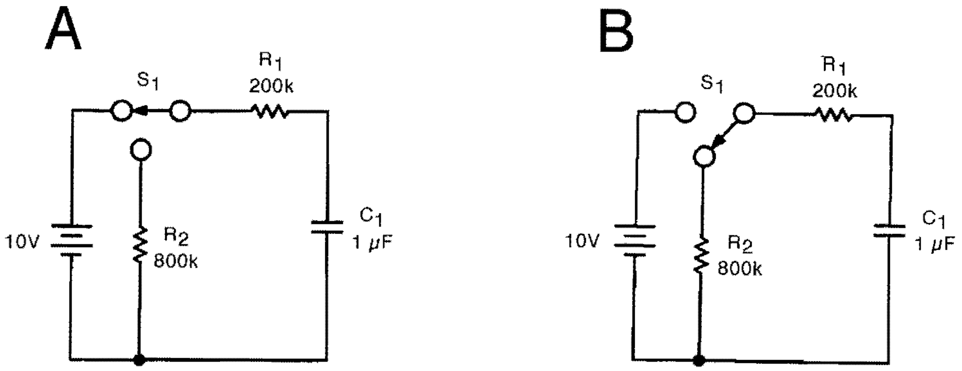


Figure 8-15
Solving time constants.

49. (200 milliseconds or 0.2 seconds) Thus, after 0.2 seconds, the charge on the capacitor is ____________ volts.

50. (6.32 volts) After 0.4 seconds, the charge on the capacitor is ____________ volts.

51. (8.65 volts) For all practical purposes, the voltage across the capacitor is 10 volts after __________ time constants.

52. (five) Assume that after the capacitor is fully charged, you switch S_1 to the position shown in Figure 8-15B. The total resistance in the discharge path is ____________ .

53. (1 megohm) Thus, the discharge time constant is ____________ .

54. (1 second) After 1 second, the charge on the capacitor is __________ volts.

55. (3.68 volts) The voltage drops to 0.5 volts after ____________ seconds.

56. (3 seconds)

EXPERIMENT 19

RC Time Constants

OBJECTIVE: *To determine experimentally how a capacitor charges and discharges through a resistor.*

Introduction

You can verify much of the information that was presented in the previous section experimentally. In this experiment, you will explore the charge and discharge characteristics of the capacitor.

Material Required

1 — Heathkit Analog Trainer
1 — Multimeter with test leads
1 — 47 µF electrolytic capacitor (#25-883)
1 — 470 µF electrolytic capacitor (#25-960)
1 — 100 Ω, 5%, 1/2-watt resistor (brown-black-brown-gold)
1 — Double-pole-double-throw (DPDT) slide switch (#60-2)
1 — Clock or watch to measure seconds
Soldering iron and solder
#22 copper (hookup) wire

Procedure

1. Connect your ohmmeter to the 100 kilohm pot between the wiper (center terminal) and the outer terminal so that the resistance of the pot increases when you rotate its knob clockwise (cw). Adjust the potentiometer until the ohmmeter indicates exactly 50 kΩ.

2. Do not disturb the setting of the potentiometer while you construct the circuit shown in Figure 8-16A. Prepare three 4-inch wires and solder these to the unused lugs on the DPDT slide switch. Only half of this switch is used in this experiment.

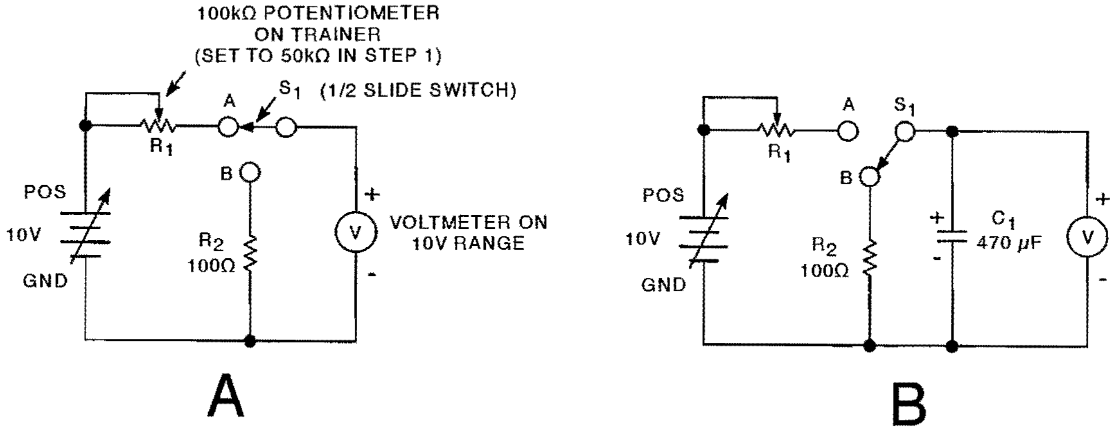

100kΩ POTENTIOMETER
ON TRAINER
(SET TO 50kΩ IN STEP 1)
A
S1 (1/2 SLIDE SWITCH)
R1
B
POS
10V
GND
R2
100Ω
+
V
-
VOLTMETER ON
10V RANGE
A
A
S1
R1
B
POS
10V
GND
R2
100Ω
+
-
C1
470 μF
+
V
-
B

Figure 8-16

Circuit for plotting the capacitor charge curve.

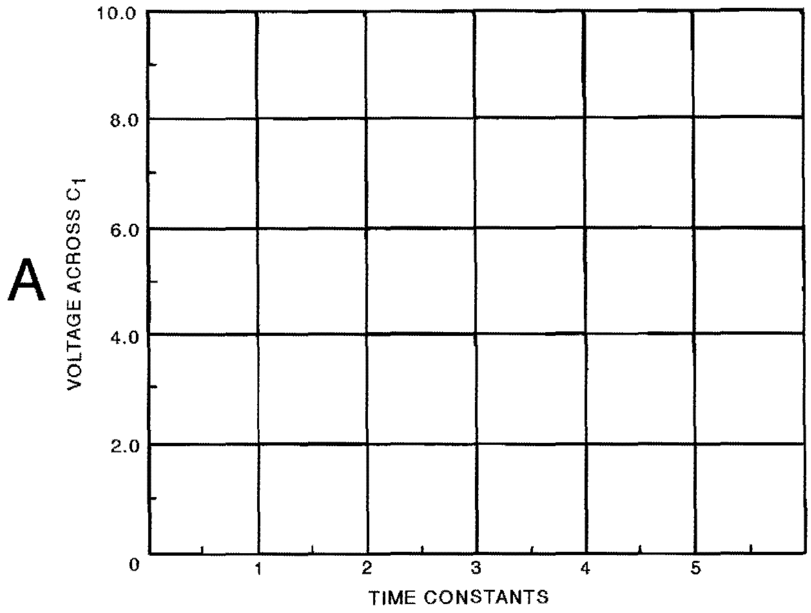
3. Switch the Trainer on and adjust the + voltage control until the voltmeter indicates exactly 10 volts. Be sure the slide switch is in the A position as shown. Note: The switch is being used as a single-pole-double-throw (SPDT) switch.

4. Locate the 470 μF capacitor. Because this is an electrolytic capacitor, you must observe its polarity when you connect it into the circuit. Add the capacitor to the circuit as shown in Figure 8-16B.

5. Set the switch to position B, as shown in Figure 8-16B, so that the capacitor discharges completely through R_2. The voltmeter should now indicate 0 volts.

6. Use the values of C_1 and R_1 to compute the RC time constant. The time constant is ____________ seconds.

7. On the grid shown in Figure 8-17A, calculate and plot the voltage you would expect to find across C_1 after it charges for intervals of 0, 1, 2, 3, 4, and 5 time constants.



B

VOLTAGE ACROSS C_1 AFTER

0 TIME CONSTANT	1 TIME CONSTANT	2 TIME CONSTANTS	3 TIME CONSTANTS	4 TIME CONSTANTS	5 TIME CONSTANTS
0.0V					

C

VOLTAGE ACROSS C_1 AFTER

0 TIME CONSTANT	1 TIME CONSTANT	2 TIME CONSTANTS	3 TIME CONSTANTS	4 TIME CONSTANTS	5 TIME CONSTANTS
10.0V					

Figure 8-17

Record the data for Experiment 19 here.

8. Use a pencil [to distinguish this curve from another you will plot later (step 11) on the same grid], connect these points to form the RC time constant charge curve. Compare this curve with curve A of Figure 8-14.

9. In this step, you will need a clock or watch to measure the length of the RC time constant. Starting at exactly 0-seconds, switch the slide switch into position A, and measure the length of time it takes for the voltage across C_1 to charge to 6.32 volts. To obtain an accurate reading, you may have to repeat this step several times and average your readings together. Be sure to discharge C_1 through R_2 (by setting the slide switch to position B) each time you repeat this step. The measured RC time constant is ____________ seconds.

10. Set S_1 to position B to discharge C_1 through R_2. While you time the process, switch S_1 to position A, and record the voltage across C_1 at intervals of 1, 2, 3, 4, and 5 time constants. For example if your measured time constant in Step 9 is 25 seconds, record the voltage across C_1 at intervals of 25, 50, 75, 100, and 125 seconds. Record these values in the table shown in Figure 8-17B. To obtain accurate readings you will probably have to repeat this step several times. Be sure you switch S_1 to discharge the capacitor through R_2 before you make each measurement.

11. Use an ink pen to plot these values on the graph shown in Figure 8-17A. Connect the plotted points to form the time constant curve.

12. Compare the ink curve you plotted in Step 11 with the pencil curve you plotted in Step 8. What do you notice about the two curves? ____________________
____.

13. Replace the 470 µF capacitor with the 47 µF capacitor. Compute the new circuit time constant, t = ____________ seconds. Use the technique described in Step 9 to measure the length of the RC time constant. The time constant is now ____________ seconds. Does this agree with your computed time constant for the new RC combination? ____________ What happens to the length of time constant when the value of capacitance decreases? ____________ .

14. Replace the 47 µF capacitor with the 470 µF capacitor. The circuit should now be in the original condition shown in Figure 8-16B.

15. Rotate the shaft of the potentiometer counterclockwise (ccw) one quarter turn. This ______________ the value of R_1.
increases/decreases

16. Repeat the procedure in Step 9 to determine the effect that this has on the RC time constant. What is the effect? __________________________________
____ .

17. Rotate the shaft of the potentiometer fully clockwise (cw). This _______________ the value of R_1. increases/decreases

18. Repeat the procedure in Step 9 to determine the effect that this has on the RC time constant. What is the effect? __________________________________
____ .

Discussion

The time constant you computed in Step 6 should be approximately 24 seconds. ($t = 470 \times 10^{-6} \times 50 \times 10^{3} = 23500 \times 10^{-3} = 23.5$ seconds). The curve you plotted in Step 8 should agree exactly with curve A in Figure 8-13. The shape of this curve is universal and should hold true for any combination of resistance and capacitance.

The curve you plotted in Step 11 should closely agree with the curve you plotted in Step 8. However, due to the crude method of timing you used and component tolerances, some errors are inevitable. Nevertheless, your measured curve should have the same general shape as your computed curve.

In Step 13 you decreased the value of C_1. This shortens the RC time constant. With the 47 μF capacitor the time constant should be approximately 2.35 seconds. Again, due to component tolerances and timing errors, your measured value may be slightly different.

In Steps 15 and 16, you saw that you could also decreasing the value of R_1 to shorten the time constant. To do this, you rotated the pot in the ccw direction. In Steps 17 and 18, you rotated the pot in the cw direction and saw that the time constant increased as the value of R_1 increased.

By now you should be quite familiar with the charge characteristics of the capacitor. Next, you will examine the discharge characteristics.

Procedure (Continued)

19. Disconnect the circuit in Figure 8-16. Connect your ohmmeter across the 100 kilohm pot as shown in Figure 8-18. Adjust the potentiometer until the ohmmeter indicates exactly 20 kΩ.

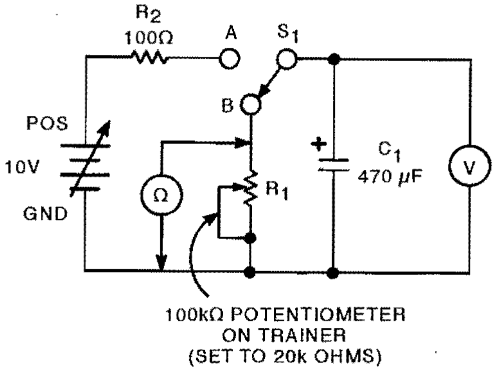


Figure 8-18

Circuit for plotting the discharge curve.

20. Do not disturb the (20 kΩ) setting of the pot while you construct the circuit shown in Figure 8-18. Be sure to observe the polarity when you connect the 470 μF capacitor.

21. Set S_1 to position A and allow C_1 to quickly charge through R_2. Adjust the + voltage control until the voltage across the capacitor is exactly 10 volts.

22. If you set the switch to position B, C_1 will discharge through R_1. Use the values of C_1 and R_1 to compute the length of the RC time constant. The time constant is ____________ seconds.

23. On the grid shown in Figure 8-17A, plot the voltage you would expect to find across C_1 after it discharges for intervals of 0, 1, 2, 3, 4, and 5 time constants.

24. Use a pencil to connect these points to form the RC time constant discharge curve. Compare this curve with curve B of Figure 8-14.

25. In this step you will measure the RC time constant in the same way you did earlier. When C_1 is fully charged, be ready to switch S_1 to position B so that C_1 can discharge through R_1. Now switch S_1 and measure the length of time that it takes for C_1 to discharge to 3.68 volts. The RC time constant you measured is ____________ seconds. How does this compare with the value you computed in Step 22? ____.

26. Measure the voltage across C_1 after it discharges at intervals of 1, 2, 3, 4, and 5 time constants. Record the values in the table shown in Figure 8-17C.

27. Plot these values on the graph in Figure 8-17A. Use an ink pen to connect the plotted points to form the time constant discharge curve.

28. Compare the ink curve you plotted in Step 27 with the pencil curve you plotted in Step 24. What do you observe? ________________________________ ____.

29. Increase and decrease the value of R_1 to verify that the time constant is directly proportional to the value of R_1. As you did in step 25, measure the time constant each time you change R_1. Can you see that the time constant is directly proportional to the value of R_1? ________
(yes/no)

30. Switch the Trainer off.

Discussion

The two discharge curves should closely correspond to each other and to the ideal discharge curve shown earlier in Figure 8-14. The possibility of error is greater in the discharge experiment than in the earlier charging experiment. There are two reasons for this. First, the time constant is shorter and therefore more difficult to measure accurately. Second, the meter affords a second discharge path for C_1. Thus, the capacitor discharges through R_1, and the meter, in parallel. Unless you use an electronic (high input impedance) type voltmeter, this can cause an error of almost ten percent. Your computed time constant should be 9.4 seconds: ($470 \times 10^{-6} \times 20 \times 10^{3} = 9400 \times 10^{-3} = 9.4$ seconds). Your measured value should be close to this, but component tolerances, time measurement errors, and meter loading, do introduce some inaccuracy.

CAPACITORS IN COMBINATION

Like resistors, capacitors can be connected in various combinations. Thus, you should study how capacitors behave when they are connected together in different ways.

Capacitors in Parallel. Figure 8-19A shows the dimensions of the 225 pF capacitor that was described earlier. In Figure 8-19B, two of these capacitors are connected in parallel. Of the three factors which determine capacitance, only one has changed. The dielectric constant and the spacing between the plates are the same as before. However, the effective area of the two plates has increased. In fact, the area has doubled. Recall that capacitance is directly proportional to the area of the plates. Therefore, the total capacitance is twice that of the single capacitor.

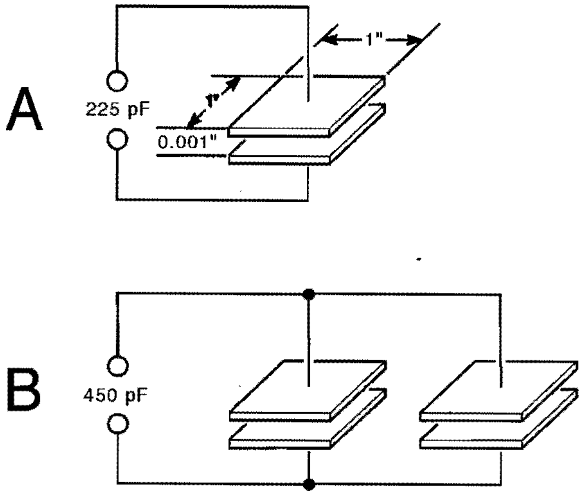


Figure 8-19
Connecting capacitors in parallel increases capacitance.

This shows that connecting capacitors in parallel is equivalent to adding the plate areas. Consequently, the total capacitance is equal to the sum of the individual capacitance values. If three capacitors are connected in parallel, you add the individual values to find the total capacitance (C_T) :

$$C_T = C_1 + C_2 + C_3$$

If $C_1 = 5\ \mu F$, $C_2 = 10\ \mu F$, and $C_3 = 1\ \mu F$; then $C_T = 16\ \mu F$. Notice that capacitors in *parallel* add like resistors in *series*.

Capacitors that are connected in parallel all charge to the same voltage. Remember that the voltage is the same across every section of a parallel network.

Capacitors In Series. Figure 8-20 compares the "standard" capacitor with two "standard" capacitors that are connected in series. As shown, this is equivalent to doubling the thickness of the dielectric. That is, two series capacitors act like a single capacitor which has a dielectric thickness equal to the sum of the individual dielectric thicknesses. Since capacitance is inversely proportional to the spacing between the plates, doubling the thickness of the dielectric cuts the total capacitance value to one half that of the "standard" capacitor.

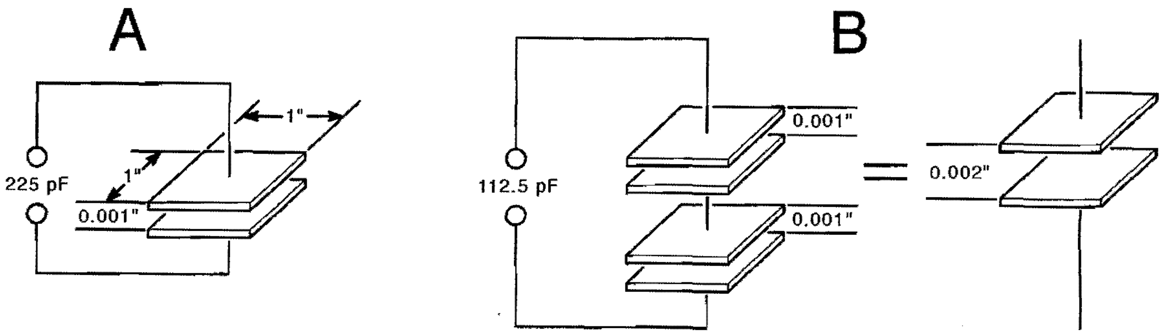


Figure 8-20

Connecting capacitors in series decreases capacitance.

You calculate the total capacitance of a group of series capacitors in the same way as you calculate the total resistance of resistors in parallel. Or stated more simply; capacitors in series combine in the same way as resistors in parallel. You can use the following formula to calculate the total capacitance of two capacitors in series:

$$C_T = \frac{C_1 \times C_2}{C_1 + C_2}$$

Note that this equation has the same form as the equation for calculating two resistors in parallel.

When more than two capacitors are connected in series, you use the following formula:

$$C_T = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots}$$

Here again, the equation has the same form as the one learned about earlier for calculating total resistance in parallel circuits.

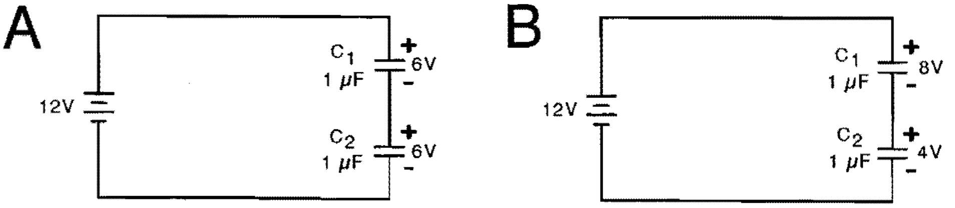


Figure 8-21
Voltage distribution across capacitors in series.

Figure 8-21 shows two capacitors connected in series across a 12-volt battery. An interesting thing about capacitors in series is the way in which the applied voltage is distributed across the capacitors. If the two capacitors have the same value, the applied voltage is distributed evenly between the two. In Figure 8-21A, each capacitor charges to one half the applied voltage or to 6 volts.

However, when the capacitors have different values, an interesting thing happens. The smaller capacitor charges to a higher voltage than the larger capacitor. In Figure 8-21B, C_2 is twice as large as C_1. Therefore C_1 charges to twice the voltage. Since the total voltage across both capacitors must be 12 volts, C_1 must drop 8 volts while C_2 drops only 4 volts.

To understand why the voltage is distributed in this way, you must recall an earlier equation which expresses capacitance in terms of charge and voltage. The equation is:

$$C = \frac{Q}{E}$$

Where C is capacitance in farads, Q is the charge in coulombs, and E is in volts. You can rearrange this equation like this:

$$E = \frac{Q}{C}$$

In this form, the equation states that the voltage across the capacitor is directly proportional to the charge on the capacitor, but inversely proportional to the size of the capacitor. In Figure 8-21B, the two capacitors are in series. Consequently, the charging current is the same at all points in the circuit. For this reason, the two capacitors must always have equal charges. Since the charges are equal, the voltage is determined solely by the value of the capacitor. And since the voltage is inversely proportional to the capacitance value, the smaller capacitor charges to a higher voltage.

Programmed Review

57. The formula for determining the total capacitance of three capacitors in parallel is ____________ .

58. ($C_T = C_1 + C_2 + C_3$) If the three capacitors are all 6 µF, the total capacitance is ____________ .

59. (18 µF) If the same three capacitors are connected in series, the total capacitance is ____________ .

61. ($C_T = \dfrac{1}{\frac{1}{C_1} + \frac{1}{C_1} + \frac{1}{C_3}}$)

When two capacitors that have different values are connected in series, the ___________ capacitor charges to the higher voltage.
larger/smaller

62. (Smaller).

EXPERIMENT 20

Series and Parallel Capacitors

OBJECTIVES: *To demonstrate how voltage is distributed between series capacitors.*

To demonstrate how total capacitance is affected when you connect capacitors in series and parallel.

Introduction

The previous section made several important points regarding capacitors in a series/parallel combination. In this experiment, you will verify three of these points.

Material Required

1 — Heathkit Analog Trainer
1 — Multimeter with test leads
1 — 10 µF electrolytic capacitor
1 — 47 µF electrolytic capacitor
1 — 470 µF electrolytic capacitor
1 — 100 Ω, 5%, 1/2-watt resistor (brown-black-brown-gold)
1 — Double-pole-double-throw (DPDT) slide switch (#60-2)
1 — Watch or clock capable of measuring seconds
#22 copper (hook-up wire

Procedure

1. Switch the Trainer ON and adjust the +voltage control on the Trainer for an indication of 10 volts between the POS and GND terminals. Switch the Trainer OFF.

2. Construct the circuit shown in Figure 8-22. Be sure to observe polarity when you connect the capacitors.

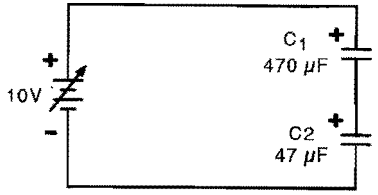


Figure 8-22
Circuit for determining the voltage distribution between capacitors in series.

3. Switch the Trainer on and measure the voltage across capacitor C_2. The voltage drop is ____________ volts.

4. Calculate the voltage drop across capacitor C_1. To do this, subtract the voltage drop across capacitor C_2 from the applied voltage. The voltage drop across capacitor C_1 is ____________ volts.

5. When two capacitors of unequal value are connected in series, which one charges to the higher voltage? ____________ .

   Repeat this segment of the experiment with the 470 µF and the 10 µF capacitors connected in series.

Discussion

This experiment illustrates how the applied voltage is distributed across series capacitors. You found that the smaller capacitor charges to a higher voltage than the larger capacitor. The voltage across the 470 µF capacitor should be approximately 0.9 volts while the voltage across the 47 µF capacitor should be 9.1 volts. Component tolerance and voltmeter loading do introduce errors as before. The sum of the voltages across the capacitors is equal to the applied voltage.

You will now learn how total capacitance is affected when you connect capacitors in series.

Procedure (Continued)

6. Disconnect the circuit on the Trainer breadboard, and construct the circuit shown in Figure 8-23A. Set switch S_1 to position A. Adjust the 100 kΩ potentiometer to place exactly 50 kΩ between the +POS voltage terminal and point A on the slide switch. Adjust the +POS voltage control until the meter indicates exactly 10 volts.

7. Add the 470 µF capacitor to the circuit as shown in Figure 8-23B. Switch S_1 to position B so that C_1 can completely discharge.

8. In this step, you will need a watch or clock to time how long it takes C_1 to charge to 6.32 volts. With your timer zeroed, set switch S_1 to position A, and time the charge of C_1. The voltage across C_1 reaches 6.32 volts after ____________ seconds. This is one time constant.

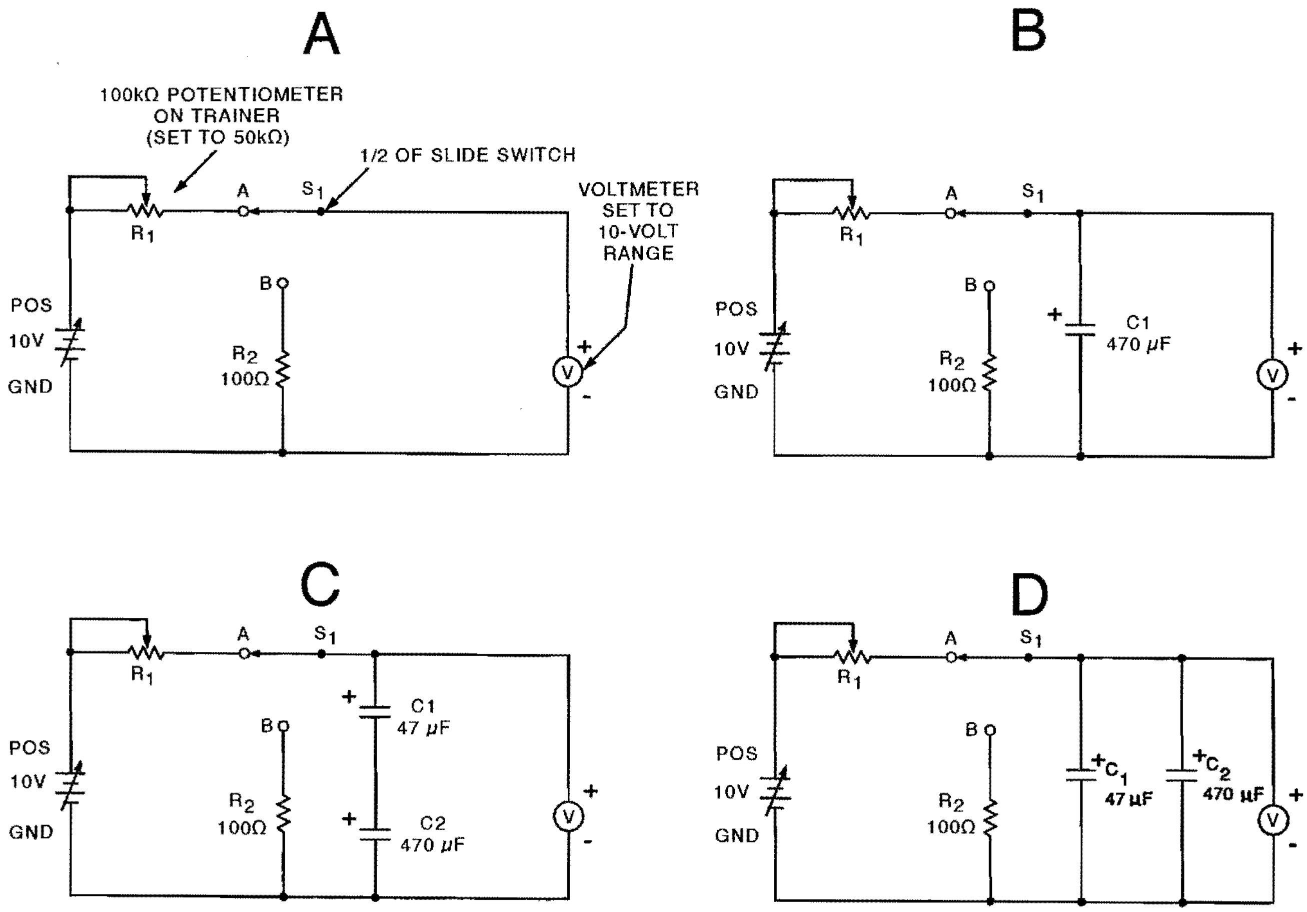

A
100kΩ POTENTIOMETER ON TRAINER (SET TO 50kΩ)
1/2 OF SLIDE SWITCH
VOLTMETER SET TO 10-VOLT RANGE
A
S1
R1
B
POS
10V
GND
R2 100Ω
V
B
C1 470 μF
C
C1 47 μF
C2 470 μF
D
C1 47 μF
C2 470 μF

Figure 8-23

Experimenting with capacitors in series and in parallel.

9. Now connect the 47 μF capacitor (C_2) in series with C_1 as shown in Figure 8-23C. Switch S_1 to the B position so that the capacitors can completely discharge.

10. With your timer zeroed, switch S_1 back to position A, and measure the time it takes for C_1 and C_2 (in series) to charge to 6.32 volts. The time is seconds.

11. What happened to the length of the time constant? ____________________

    ____.

    Why? ____.

    What assumption can you make concerning capacitors in series? ________

    ____.

Discussion

In Step 8 the 470 µF capacitor charges through 50 k ohms of resistance. Thus, the time constant should be about 23.5 seconds. In Step 9, the 47 µF capacitor is connected in series with the 470 µF capacitor. In Step 10, you saw that this resulted in a much shorter time constant. Because the value of R_1 remained constant at 50 k, the value of the total capacitance *must* have decreased. This demonstrates that **total capacitance decreases when capacitors are connected in series.** The total capacitance of the two capacitors in series is:

$$C_T = \frac{470 \times 47}{470 + 47} = \frac{22090}{517} = 42.73\ \mu F$$

The time constant with this combination should, therefore, be approximately 2.14 seconds.

In the next part of this experiment, you will now find out what happens when capacitors are connected in parallel.

Procedure (Continued)

12. Reconstruct the circuit shown in Figure 8-23B.

13. In Step 8, you measured the time constant of this circuit. Repeat Step 8 several times, and carefully note the length of the time constant. Be sure to completely discharge C_1 before you make each measurement. The measured time constant is ____________ seconds.

14. Add the 47 µF capacitor (C_2) in parallel with C_1, as shown in Figure 8-23D. Once again, carefully measure the RC time constant. It may be necessary to measure the time constant several times to obtain an accurate reading. The time constant is ____________ seconds.

15. What happened to the length of the time constant? ____________________

    ____.

    Why? ____.

    What conclusion can you make concerning capacitors connected in parallel?

    ____

    ____.

16 Switch the Trainer OFF.

Discussion

The time constant you measured in Step 13 should be about 23.5 seconds. The actual time you measured may be off by as much as 30 percent, depending upon the exact value of R_1 and C_1. However, if you carefully repeat the measurement several times, you should measure the same value each time.

In Step 14 you added the 47 µF capacitor in parallel with C_1 and carefully measured the new time constant. The new time constant should be about 10 percent (2.35 seconds) longer than the first. Because R_1 did not change, the total capacitance must have increased by about 10 percent. That is, the total capacitance must now be about 517 µF. Note that this is the sum of the values of C_1 and C_2. This demonstrates that **when capacitors are connected in parallel, the total capacitance (C_T) is the sum of the individual capacitor values.**

EXPERIMENT 21

Using Capacitors

OBJECTIVE: *To demonstrate some of the ways that capacitors are used.*

Introduction

The capacitor is a very useful device. While most of its applications involve alternating current, it does have several DC applications. In this experiment, you will examine four of these applications.

Material Required

1 — Heathkit Analog Trainer
1 — Multimeter with test leads
1 — 47 µF electrolytic capacitor
1 — 470 µF electrolytic capacitor
1 — 100 Ω, 5%, **2-watt** resistor (brown-black-brown-gold)
1 — Double-pole-double-throw (DPDT) slide switch (#60-2)
1 — Lamp socket (#434-21)
1 — Lamp (#421-16)
1 — Relay with wires attached (#69-136)
#22 copper (hookup) wire

Procedure

1. Connect the circuit shown in Figure 8-24. Switch the Trainer ON and adjust the + voltage control so that the voltage between the POS and GND terminals is 6 volts.

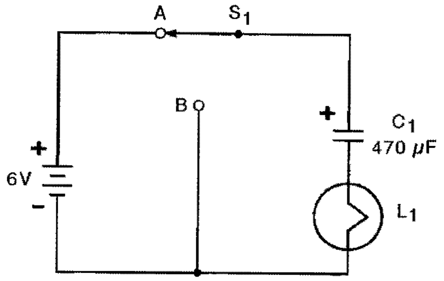


Figure 8-24

2. Switch S_1 back and forth between positions A and B. Does the lamp light? __________ Does it stay lit? __________

3. Switch S_1 to position A. After the first instant, does any current flow through the lamp? __________ Can you explain why? ____________________
____.

Discussion

In Step 2, the lamp should light momentarily each time you change the switch setting. To see why this happens, refer to Figure 8-24. When S_1 is in the A position, C_1 charges to the applied voltage (6 volts). The initial surge of current causes L_1 to light. As soon as C_1 is fully charged, all current flow ceases. Because C_1 charges very rapidly, L_1 blinks on for only an instant. Except for the initial **charging current,** the capacitor blocks the direct current. That is, C_1 prevents direct current from flowing through the lamp. **Blocking direct current is one of the most popular applications of the capacitor.**

If you now return S_1 to the B position, C_1 quickly discharges through L_1. This causes the lamp to blink again.

Following is another application.

Procedure (Continued)

4. Disconnect the previous circuit. Construct the circuit shown in Figure 8-25A. Close S_1 and adjust the + voltage control on the experimenter until the meter reads exactly 10 volts.

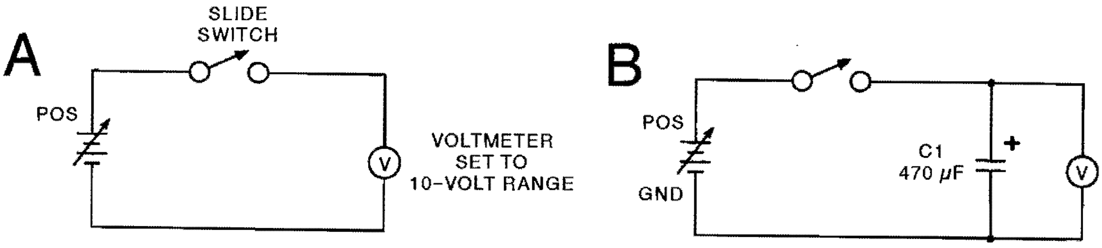


Figure 8-25
The capacitor converts pulsating DC to direct current.

5. Open and close the switch about once a second and note the action of the meter. The type of voltage that is now being applied to the meter is called pulsating DC. It is direct current which is being turned on and off. Note that the meter reading quickly fluctuates between 0 and 10 volts.

6. Add the 470 µF capacitor (C_1) in parallel with the meter as shown in Figure 8-25B.

7. Open and close the switch about once a second and note the action of the meter. Does the meter behave differently than it did in Step 5? ______________
____.

Discussion

The preceding steps demonstrate another purpose of the capacitor. You can use the capacitor to convert pulsating DC to fairly steady direct current. In Step 5, the meter fluctuates between 0 and 10 volts. However, once you add the capacitor, the voltage remains fairly constant at 10 volts. When you close the switch, the capacitor charges. When you open the switch, the capacitor discharges into the load (the meter) and thereby maintains a steady output. Direct current power supplies use this technique to convert pulsating DC to a constant voltage level. In this application, high value (1000 µF or more) electrolytic capacitors are referred to as *filter* capacitors.

Following is another capacitor application that is sometimes used in DC power supplies.

Procedure (Continued)

8. Disconnect the previous circuit. Use the +POS voltage control to set the voltage between the POS and GND terminals to 5 volts.

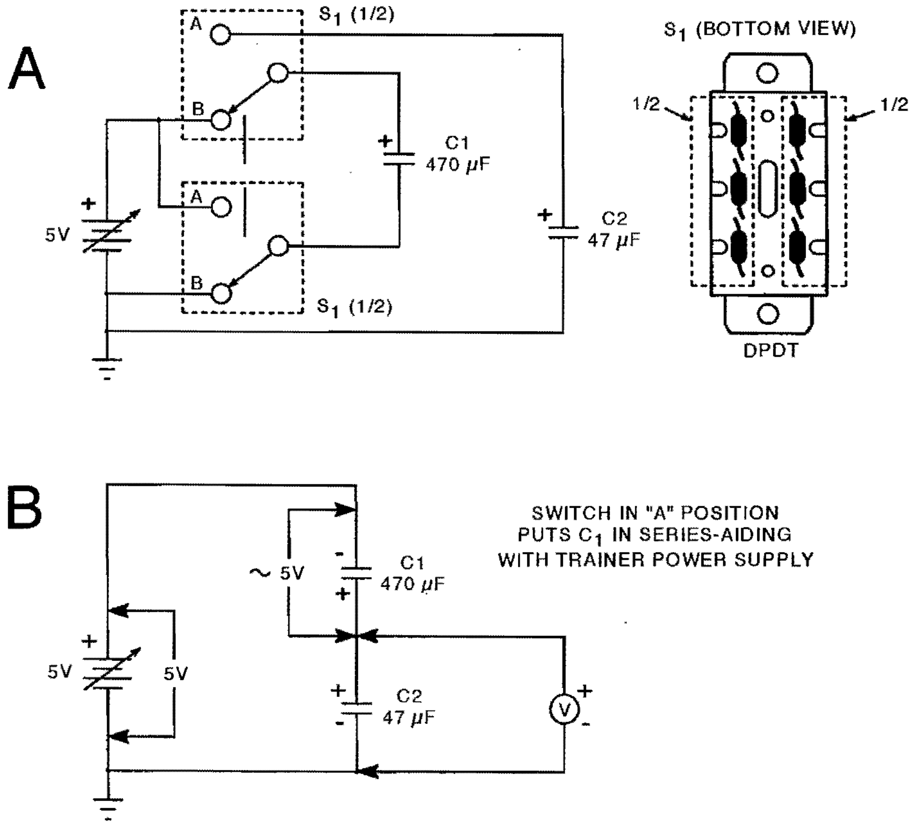
9. Construct the circuit shown in Figure 8-26A.

10. With S_1 set to the B position, note that voltage is only applied to C_1. Measure the voltage across C_1. The voltage is ____________ volts.

11. Switch S1 to the A position, note that this places the applied voltage across both C_1 and C_2 in series. Measure the voltage across C_2. The voltage across C_2 is ____________ V.

    How do you account for the fact that the voltage across C_2 is higher than the voltage applied to the circuit? ______________________________
    ____.

    Where did the extra voltage come from? ______________________________
    ____.



SWITCH IN "A" POSITION
PUTS C_1 IN SERIES-AIDING
WITH TRAINER POWER SUPPLY

Figure 8-26

Capacitors used as a voltage doubler.

Discussion

This part of the experiment demonstrates the operation of a circuit that is called a voltage doubler. When S_1 is in position B, C_1 is connected directly across the power supply. Therefore C_1 charges to 5 volts. Now, when you switch S_1 to position A, the 5 volts across C_1 is in series with the 5-volt power supply. Thus, the total voltage from the positively polarized end of C_1 to the GND terminal approaches 10 volts. This is shown in Figure 8-26B. With S_1 in position A, C_2 is in a series combination of C_1 and the power supply. Consequently, C_2 charges to almost 10 volts. The net effect is that the applied voltage (nearly) doubles.

A circuit which performs in a similar manner is commonly used in power supplies. The mechanical switch (S_1) is replaced with an electronic switch that consists of two or more semiconductor devices called *diodes.**

Now consider one final application of the capacitor.

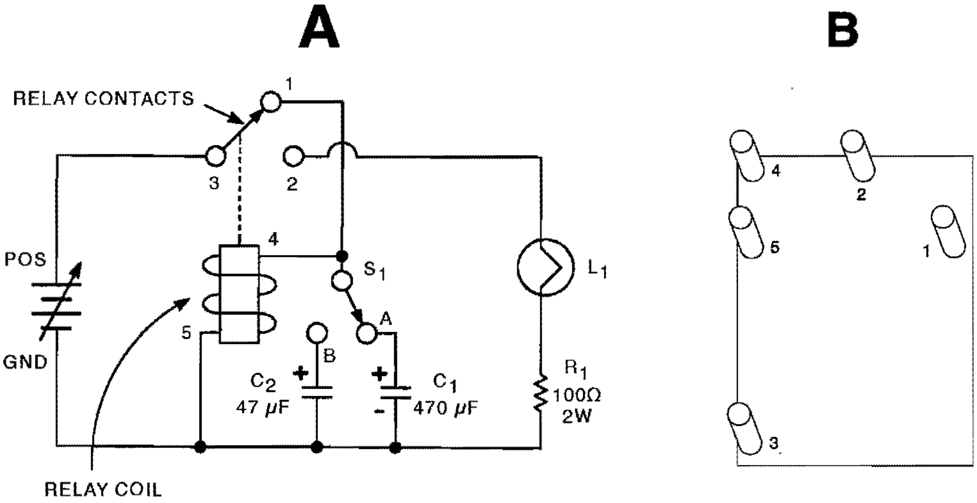


Figure 8-27
Capacitors are used for timing.

Procedure (Continued)

12. Disconnect the previous circuit. Turn the + voltage control to its minimum voltage position.

13. Construct the circuit shown in Figure 8-27A. Because this circuit is relatively complex, you are given a wiring diagram in Figure 8-28. However, you should not resort to this diagram unless it is absolutely necessary. Wire the circuit from the schematic then check it against Figure 8-28. Figure 8-27B reminds you how the relay pins are numbered.

14. Set the slide switch (S_1) to position A so that C_1 is connected in parallel with the relay coil.

15. Slowly increase the + voltage control until the relay energizes and causes L_1 to light. Continue to increase the voltage slowly until the lamp blinks on and off at a regular rate. Do not increase the voltage beyond this point.

---

* NOTE: The characteristics, use, and application of diodes is covered thoroughly in the Heathkit Educational Systems' course, *Semiconductor Devices.*

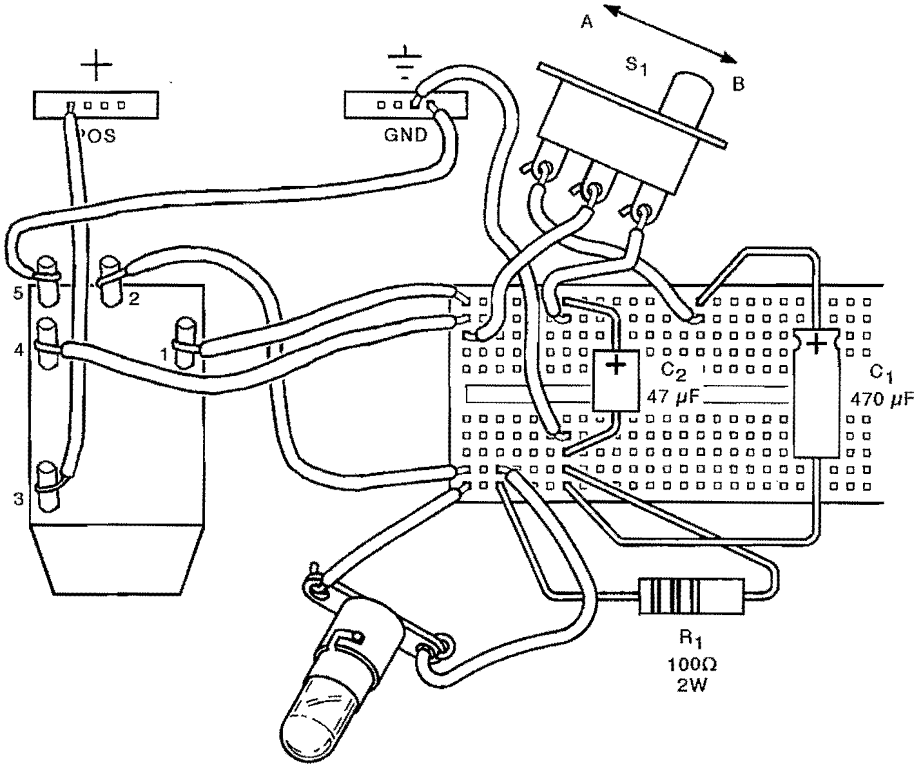


Figure 8-28

Wiring diagram for the blinker circuit.

16. To demonstrate C_1's contribution to the circuit, momentarily disconnect one end of C_1 from the circuit. What happens to the relay? Does L_1 continue to blink? ____________________ .

17. Reconnect C_1 to the circuit, and note the rate at which L_1 blinks on and off. After you disconnected C_1 (in the previous step) it may be necessary to momentarily increase the +POS voltage control to a point *higher* than its original setting to make the relay to trigger. After the relay triggers, you can decrease the +POS voltage control to its previous level; that is, just high enough to keep L_1 blinking at a constant interval.

18. Switch S_1 to position B. What happens to the rate at which L_1 blinks? ______
____ .

19. Analyze the schematic diagram of the blinker circuit and determine how it operates. Describe its operation. ______________________________
____
____
____
____ .

20. Switch the Trainer OFF.

Discussion

The blinker circuit demonstrates how you can use a capacitor for timing purposes. As you increased the power supply voltage in Step 15, current began to flow through the relay coil. At the same time, C_1 began to charge to the applied voltage. Since there is no resistance in the charge path, C charges very rapidly.

At some point, the applied voltage forces enough current through the coil to cause the relay to energize. When this happens, pin 3 of the relay pulls down to make contact with pin 2. Thus, the power supply is disconnected from the coil and is connected to the lamp circuit. Consequently L_1 lights.

When the power supply is disconnected from the relay coil, you might expect the relay to immediately de-energize. However, this does not happen due to the action of C_1. As soon as power is removed, C_1 begins to discharge through the relay coil. This provides a holding current which keeps the relay energized for a fraction of a second. After a short time, C_1 discharges to the point that it can no longer provide a strong enough holding current and the relay de-energizes.

When pin 3 of the relay falls back to pin 1, the power supply is once again connected across the coil. This causes the relay to energize again and the cycle repeats. The length of time that is required for C_1 to discharge through the relay coil is determined by the value of C_1 and the resistance of the relay coil. If you decrease the value of the capacitor, the cycle speeds up. In Step 18, you switched C_2 into the circuit instead of C_1. C_2 has about one tenth the capacitance of C_1. Thus, the cycle becomes about ten times faster.

SUMMARY

When current flows through a conductor, a magnetic field builds up around the conductor. As the magnetic field builds up, a voltage is induced into the conductor. The induced voltage opposes the applied voltage and is called a counter EMF. The process by which the counter EMF is produced is called self-induction.

The polarity of the counter EMF always opposes changes in current. It opposes the increase in current which occurs when you apply power to a circuit. It also opposes the decrease in current which occurs when you remove power. The ability of a device to oppose a change of current is called inductance. The unit of inductance is the Henry.

A device that is designed to have a specific inductance is called an inductor. It consists of turns of wire that are wrapped around a core. The greater the number of turns and the higher the permeability of the core, the greater the value of inductance.

A capacitor consists of two metal plates that are separated by an insulator called a dielectric. It has the ability to store an electrical charge. This ability to store a charge is called capacitance. When a capacitor is connected to a voltage source, it charges to the value of the applied voltage. If you then connect the charged capacitor across a load, it discharges through the load.

The unit of capacitance is the farad (F), although the microfarad (μF) and the picofarad (pF) are used more often. Three factors determine the value of a capacitor. They are: the area of the plates, the spacing between the plates, and the dielectric constant.

There are many different types of capacitors. They are generally classified by their dielectric. The most popular types are air, paper, mica, ceramic, and electrolytic.

The capacitance and the resistance in the circuit determine the length of time that is required for a capacitor to charge. A time constant is the length of time that is required for a capacitor to charge to 63.2 percent of its applied voltage. The formula to find the time constant is:

$$t = R \times C$$

You use a time constant chart when you work with time constants. It shows the manner in which capacitors charge and discharge. It plots the number of time constants against the percent of the applied voltage.

Capacitors may be connected in series or in parallel. When they are connected in parallel, the total capacitance is equal to the sum of the individual capacitor values. The formula is:

$$C_T = C_1 + C_2 + C_3$$

When they are connected in series, you can determine the total capacitance with the following formula:

$$C_T = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots}$$

UNIT EXAMINATION

1. The amount of inductance which induces an EMF of 1 volt into a conductor when the current changes at a 1 ampere per second rate is defined as one:

   A. henry.
   B. farad.
   C. millihenry.
   D. microfarad.

2. Which of the following does *not* increase the inductance value of a coil?

   A. Increasing the number of turns of wire on the coil.
   B. Inserting a soft iron core.
   C. Inserting a core which has high permeability.
   D. Increasing the current through the coil.

3. A counter EMF is a voltage that:

   A. forces current counterclockwise in the circuit.
   B. opposes the applied EMF.
   C. aids the applied EMF.
   D. cancels the applied EMF.

4. An inductor stores electrical energy in the form of:

   A. an electrostatic field.
   B. a magnetic field.
   C. an excess of electrons at one terminal and a surplus at the other.
   D. a counter EMF.

5. Which of the following decreases the value of a capacitor?

   A. Increasing the area of the plates.
   B. Increasing the thickness of the dielectric.
   C. Decreasing the spacing between the two plates.
   D. Increasing the dielectric constant.

6. A capacitor which stores a charge of one millionth of a coulomb when an EMF of one volt is applied has a value of:

   A. 1 farad.
   B. 1 microfarad.
   C. 1 henry.
   D. 1 millihenry.

7. Refer to Figure 8-29. What is the time constant of this circuit?

   A. 1 microsecond.
   B. 1 second.
   C. 2 seconds.
   D. 0.5 second.

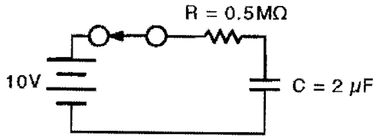


Figure 8-29
Circuit for Questions 7 and 8.

8. Refer again to Figure 8-29. Two seconds after you close the switch, what is the voltage across the capacitor?

   A. 6.32 volts.
   B. 3.68 volts.
   C. 8.65 volts.
   D. 1.35 volts.

9. What is the total capacitance of the circuit shown in Figure 8-30A?

   A. 0.66 μF.
   B. 1 μF.
   C. 2 μF.
   D. 3 μF.

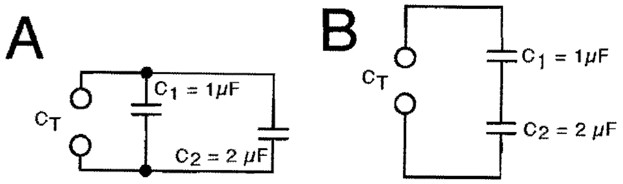


Figure 8-30
Circuit for Questions 9 through 12.

10. What is the total capacitance of the circuit shown in Figure 8-30B?

   A. 0.66 μF.
   B. 1 μF.
   C. 2 μF.
   D. 3 μF.

11. If you connect the network shown in Figure 8-30B across a 9-volt battery, C_1 charges to:

    A. 9 volts.
    B. 3 volts.
    C. 4.5 volts.
    D. 6 volts.

12. The network shown in Figure 8-30A is charged to 10 volts and is then allowed to discharge through a 1 megohm resistor. What is the charge on the capacitor after it discharges for 3 seconds?

    A. 6.32 volts.
    B. 3.68 volts.
    C. 8.65 volts.
    D. 1.35 volts.

13. You can increase the inductance of an inductor in two ways. These are:

    A. increasing the number of turns in the inductor and winding the coil around an air core.
    B. increasing the number of turns in the inductor and winding the coil around an iron core.
    C. decreasing the number of turns in the inductor and winding the coil around an air core.
    D. decreasing the number of turns in the inductor and increasing the size of the air core.

14. How long does it take for the current in the circuit shown in Figure 8-31 to reach 63.2% of its maximum value?

    A. 1 µs.
    B. 1 ms.
    C. 10 s.
    D. 100 s.

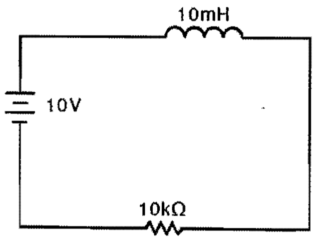


Figure 8-31

15. If you disregard the resistance of the coil, what is the current through the inductor shown in Figure 8-31 after 2 time constants?

    A. .865 μA.
    B. .865 mA.
    C. .865 A.
    D. 8.65 A.

16. What is the total inductance of a circuit if three 15 mH inductors are connected in series in the circuit?

    A. 5 mH.
    B. 15 mH.
    C. 45 mH.
    D. You cannot determine the total inductance from the information given.

17. What is the total inductance of a circuit that contains four 60 mH inductors connected in parallel?

    A. 15 mH.
    B. 60 mH.
    C. 240 mH.
    D. You cannot determine the total inductance from the information given.

18. Refer to Figure 8-32. What is the total inductance of the circuit in this Figure?

    A. 10 mH.
    B. 15 mH.
    C. 20 mH.
    D. 30 mH.

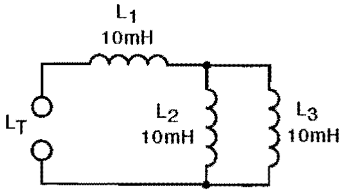


Figure 8-32

EXAMINATION ANSWERS

1. A — The Henry is the amount of inductance which induces an EMF of 1 volt into a conductor or coil when the current changes at the rate of 1 ampere per second.

2. D — The inductance value of a coil is determined by its physical construction. The current through the coil does not change the value of the inductor.

3. B — A counter EMF opposes the applied voltage.

4. B — In an inductor, energy is stored in the form of a magnetic field.

5. B — Increasing the thickness of the dielectric increases the spacing between the plates and therefore decreases the value of the capacitor.

6. B — By definition, a farad is the amount of capacitance that stores a charge of one coulomb when one volt is applied. Consequently, a capacitor which stores one millionth of a coulomb when one volt is applied must have a value of one microfarad.

7. B — $t = R \times C$
   $t = 0.5\ \text{M}\Omega \times 2\ \mu\text{F}$
   $t = 1$ second

8. C — Two seconds are equal to two time constants. Therefore the capacitor charges to 86.5 percent of the applied voltage or to 8.65 volts.

9. D — $C_T = C1 + C2$
   $C_T = 1\ \mu\text{F} + 2\ \mu\text{F}$
   $C_T = 3\ \mu\text{F}$

10. A — $C_t = \dfrac{C_1 \times C_2}{C_1 + C_2}$

$$C_t = \frac{1\ \mu\text{F} \times 2\ \mu\text{F}}{1\ \mu\text{F} + 2\ \mu\text{F}}$$

$$C_t = \frac{2}{3}$$

$$C_t = 0.66\ \mu\text{F}$$

11. D — When capacitors are connected in series, they charge to a voltage inversely proportional to their size. The small capacitor charges to a higher voltage. Since C_1 is one half the size of C_2, C_1 charges to twice the voltage of C_2. Because the applied voltage is 9 volts, C_1 charges to 6 volts and C_2 charges to 3 volts.

12. B — The total capacitance in Figure 8-30A is 3 μF. If it discharges through a 1 megohm resistor, the time constant is:

$$t = R \times C$$
$$t = 1\,M\Omega \times 3\,\mu F$$
$$t = 3 \text{ seconds}$$

If it charges to 10 volts and is allowed to discharge for 3 seconds (1 time constant), the voltage drops by 63.2 percent or to 3.68 volts.

13. B — Increasing the number of turns in the inductor dramatically increases the strength of the field produced by an inductor. In addition, a highly permeable iron core further increases the inductance of an inductor.

14. A — The time constant for an inductor is the time it takes for the current through the inductor to reach 63.2% of its maximum value. In the case of problem 14, you use the following equation to determine the time constant:

$$t = L/R$$

or

$$t = .01/10000 = .000001 \text{ sec}$$

15. B — You use Ohm's Law to determine the maximum current through the circuit. This is:

$$I = E/R$$

or

$$I = 10/10000 = .001 \text{ A}$$

Now, if you refer to the chart in Figure 8-14, you see that after 2 time constants, the current equals 86.5% of the maximum current. (Although the chart is presented to help you determine the voltage values for capacitors after a given number of time constants, you can also use the chart to determine current through inductors.) Now, determine the current after 2 time constants like this:

$$.001 \times .865 = .865 \text{ mA}$$

16. C — The inductance of inductors in series is additive. You can use the following formula to determine inductance in series:

$$L_T = L_1 + L_2 + L_3$$

or

$$L_T = 15 \text{ mH} + 15 \text{ mH} + 15 \text{ mH} = 45 \text{ mH}$$

17. A — You can use the following equation to determine the inductance in parallel:

$$L_T = \frac{1}{\frac{1}{60} + \frac{1}{60} + \frac{1}{60} + \frac{1}{60}} = 15 \text{ mH}$$

18. B — To solve this problem, first determine the inductance of the two parallel inductors with the formula:

$$L_T = \frac{L \times L}{L + L}$$

or

$$L_T = \frac{10 \times 10}{10 + 10} = 5 \text{ mH}$$

This inductance is in series with the inductance of L_T. Therefore:

$$L_T = 5 \text{ mH} + 10 \text{ mH} = 15 \text{ mH}$$